URBAN RAIL
NOISE ABATEMENT
Program Digest

U.S. DEPARTMENT OF TRANSPORTATION
Urban Mass Transportation Administration

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Contents

Rail transit noise is a major environmental impact.

Overview

Scope of the Problem

Noise from urban rail operations is more than just annoying. Continued exposure to high noise levels produces human stress, fatigue, and possibly irreversible hearing loss. Recent census data combined with measurements of noise from elevated tracks indicate that in New York City alone, over half a million people are exposed to noise levels unacceptable by EPA standards.

Excessive noise lessens the attractiveness of urban rail transit as an alternative mode of transportation to the automobile. Negative public reaction to noise and vibration in neighborhoods surrounding transit lines may result in adverse economic impacts, such as reduced property values, and may result in public opposition to new transit lines.

Transit operators, transit patrons, and community residents have all expressed concern over transit noise and have indicated that noise reduction should be a priority. In New York City, public reaction led to the drafting of state legislation specifically aimed at regulating transit noise. A survey of transit properties conducted to determine the research requirements of the urban rail industry showed noise to be the most frequently cited area in need of federally funded research and development. (36)[1]

There are presently about 570 route miles of rail transit lines, and about 10,000 rapid transit cars in the United States. Planned expansions and new rapid transit systems will result in the construction of about 325 additional route miles of transit line and the purchase of more than 2,000 new cars by the end of this century. These developments offer an opportunity to apply engineering knowledge in acoustics and vibration to

[1]Numbers in parentheses refer to sources listed in the bibliography.

the design of track structures and cars. For those transit systems already in place, noise abatement techniques are needed that can be easily retrofitted on existing transit structures and equipment.

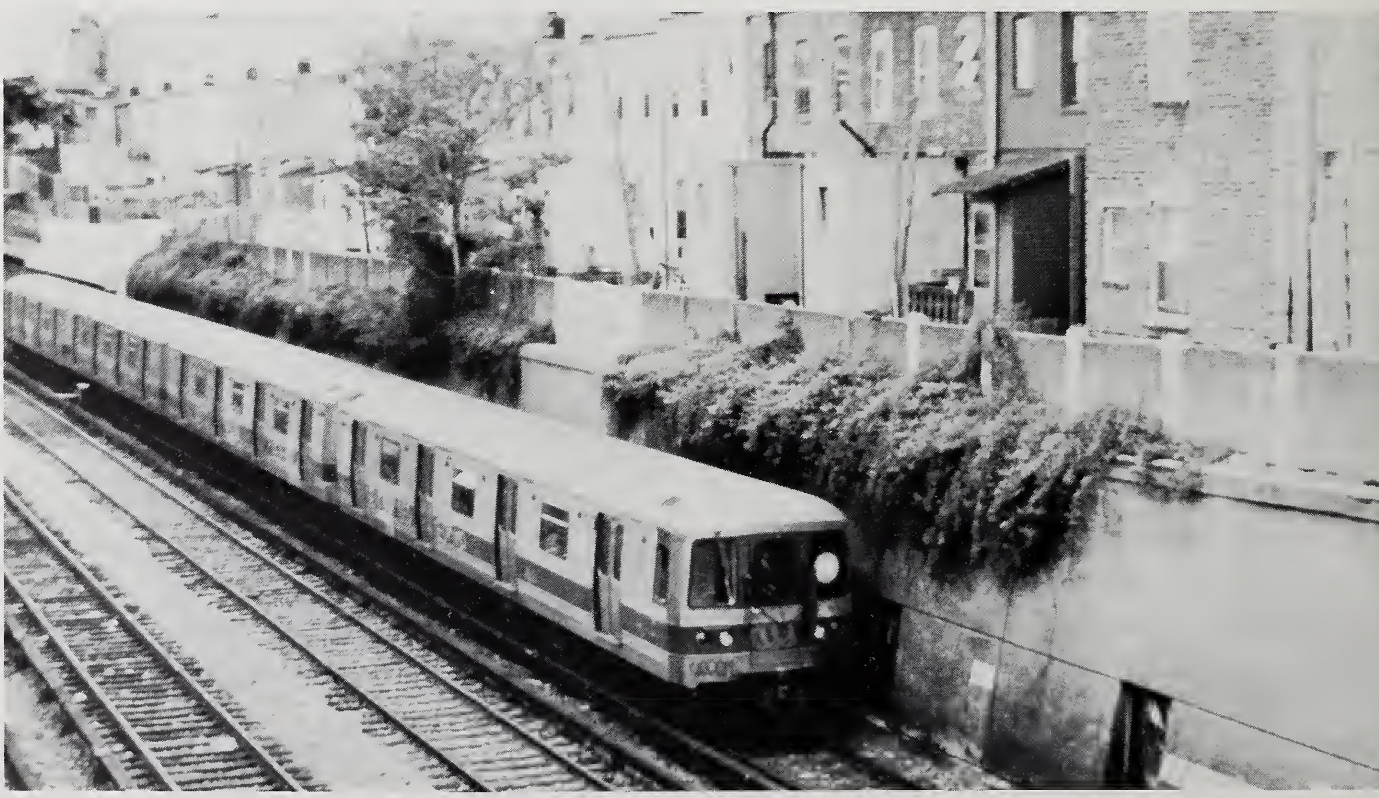
Program Development.

In response to these needs, the Urban Mass Transportation Administration (UMTA) established the Urban Rail Noise Abatement Program to assess the dimensions of the problem, to identify, develop, and test noise abatement techniques, and to share noise control technology with transit managers, suppliers, manufacturers, and others concerned with urban rail noise either professionally or as members of the general public.

The Urban Rail Noise Abatement Program provides a systematic approach to solving the urban transit noise problem. This approach has resulted in comprehensive scientific research and development projects, followed by extensive tests of applied technology. Program efforts have been explicitly designed to respond to the needs of the transit properties and to develop technologies which can be applied in many sites by addressing problems common to them all. Through carefully structured communication back and forth between transit operators, equipment manufacturers, and researchers, numerous opportunities for program review are provided in order to ensure that the program receives adequate technical, operating, and economic data, and that implementable techniques and usable products are developed and deployed.

UMTA's Office of Rail and Construction Technology gives program guidance to the Urban Rail Noise Abatement Program. The three components of the program are carried out under the technical direction of staff at the U.S. DOT Transportation Systems Center in Cambridge, Mass. These three program components are 1) assessment of the extent of the noise problem, 2) development and evaluation of technology to control noise, and 3) dissemination of the results and deployment of successful technologies. Each of these major components

Urban rail noise and vibration affect passengers, operators, and persons living in surrounding communities.



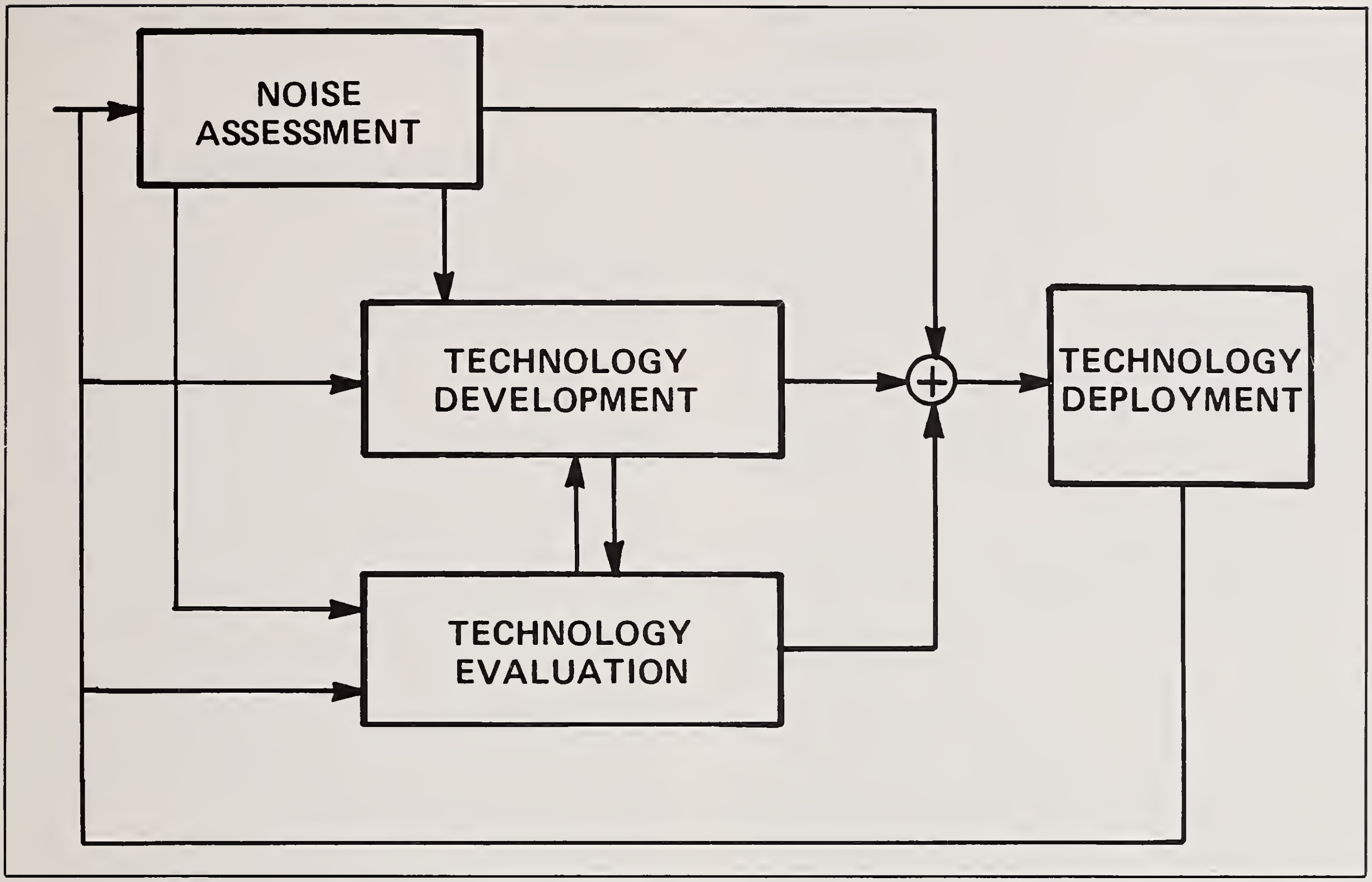


Figure 1. Relationships Among Urban Rail Noise Abatement Program Areas

has specific interrelationships with the others, and these relationships are indicated in Figure 1.

A discussion of the activities within the three major program areas forms the balance of this report. A brief description of these follows:

1. Noise Assessment

This section describes the effort to assess the extent and severity of the urban rail noise problem in the United States. When the program began, there was no comparable data on the magnitude of the noise problem in urban rail transit systems. A systematic survey was made in a standardized manner of the nine urban rail systems operating at the time, and noise levels on all these systems and their component parts were identified. The results were compared with the noise guidelines established by the American Public Transit Association (APTA), and the severity of the problem was determined. Noise abatement techniques in the current state-of-the-art were evaluated for both cost and effectiveness, and for each transit system estimates were made of the system-wide cost of reducing noise to specified levels. The results of the assessment program influenced the choices for further research, development, and evaluation, as well as the distribution of capital funds for noise abatement and control.

2. Technology Development and Evaluation

This section describes efforts to develop and evaluate improved noise control treatments. During the assessment phase, an effort was made to associate observed noise levels with specific sources and paths and to identify applicable noise abatement treatments. These efforts were subsequently extended to develop remedies for the four types of urban rail noise which were isolated and which constitute the most severe problems. These are wheel/rail noise, elevated structure noise, groundborne noise, and propulsion system noise.

The mechanisms producing noise and the paths along which it is transmitted were investigated in great detail. It was necessary to conduct this basic research into the physics of urban rail noise so that a better understanding of the specifics of its generation and transmission could lead to the development of effective noise abatement methods.

The actual cost and operating performance of noise abatement treatments are difficult to predict from experiments in the laboratory or on test tracks. In-service testing on transit systems is the only way accurately to gauge the performance of a given noise abatement procedure. Noise abatement technologies addressing the four noise categories have been and continue to be tested in transit systems throughout the country.

3. Technology Deployment

The ultimate success of the DOT program in stimulating deployment of cost-effective noise control technology is dependent on effective communication and information exchange among all those involved in reducing urban rail noise. The sharing of ideas and technological data is essential to ensure that research, development, and evaluation are directed towards producing a technology which will meet the real needs of transit operators and users. Awareness of the available technological results and products and an understanding of how they can best be applied in the transit environment is equally essential. This section outlines the mechanisms developed by the UMTA program to stimulate deployment of technology.

1. Noise Assessment

Assessment studies of nine urban rail systems were conducted to determine prevailing noise levels and to estimate costs of noise reduction. The systems studied were the Massachusetts Bay Transportation Authority (MBTA) in Boston, the Southeastern Pennsylvania Transportation Authority (SEPTA) in Philadelphia, the Port Authority Transit Corporation (PATCO) running between Philadelphia and New Jersey, the Greater Cleveland Regional Transit Authority (RTA), the Bay Area Rapid Transit District (BART) in San Francisco, the Chicago Transit Authority (CTA) and the New York City Transit Authority (NYCTA) along with the Staten Island Rapid Transit Operating Authority (SIRTOA), and the Port Authority Trans-Hudson (PATH) system operating between New York City and New Jersey. These were the U.S. rapid transit systems operating at the time. The Washington, D.C. and Atlanta systems had not yet begun operations.

Noise levels are measured inside moving transit cars as part of UMTA's assessment studies.

Assessment Methodology

As part of the assessment studies, a standard methodology was developed for measuring noise levels and for estimating the costs of noise reduction. This methodology was developed in conjunction with a pilot assessment study done on Boston's MBTA, (12) and then used in the subsequent assessments. (13-18)

Standard technical measurement procedures are important to ensure accurate measurement of noise levels. Such procedures include the type of recording equipment to be used, placement of microphones, and recording conditions. Assessment teams responsible for measuring noise on the other systems visited the MBTA. Working independently, they used the techniques developed in the pilot study to make simultaneous measurements of MBTA noise levels. The close agreement among their findings validated the measurement procedures, and ensured the compatibility of the noise measurement results for all the systems.

The measure of sound used in the assessments was the A-weighted decibel, or dBA. This measure weights the various frequencies comprising a sound in a manner which closely approximates the perceptions of the human ear. To provide the reader with a sense of the A-weighted decibel scale, Figure 2 presents transit noise levels in dBA along with noise levels of other sources affecting the typical community. The basic indicator of noise level used during the assessments was L_A (MAX), the maximum A-weighted noise level occurring over a period of time.

In the assessment methodology, noise was categorized by source (where the noise origi-

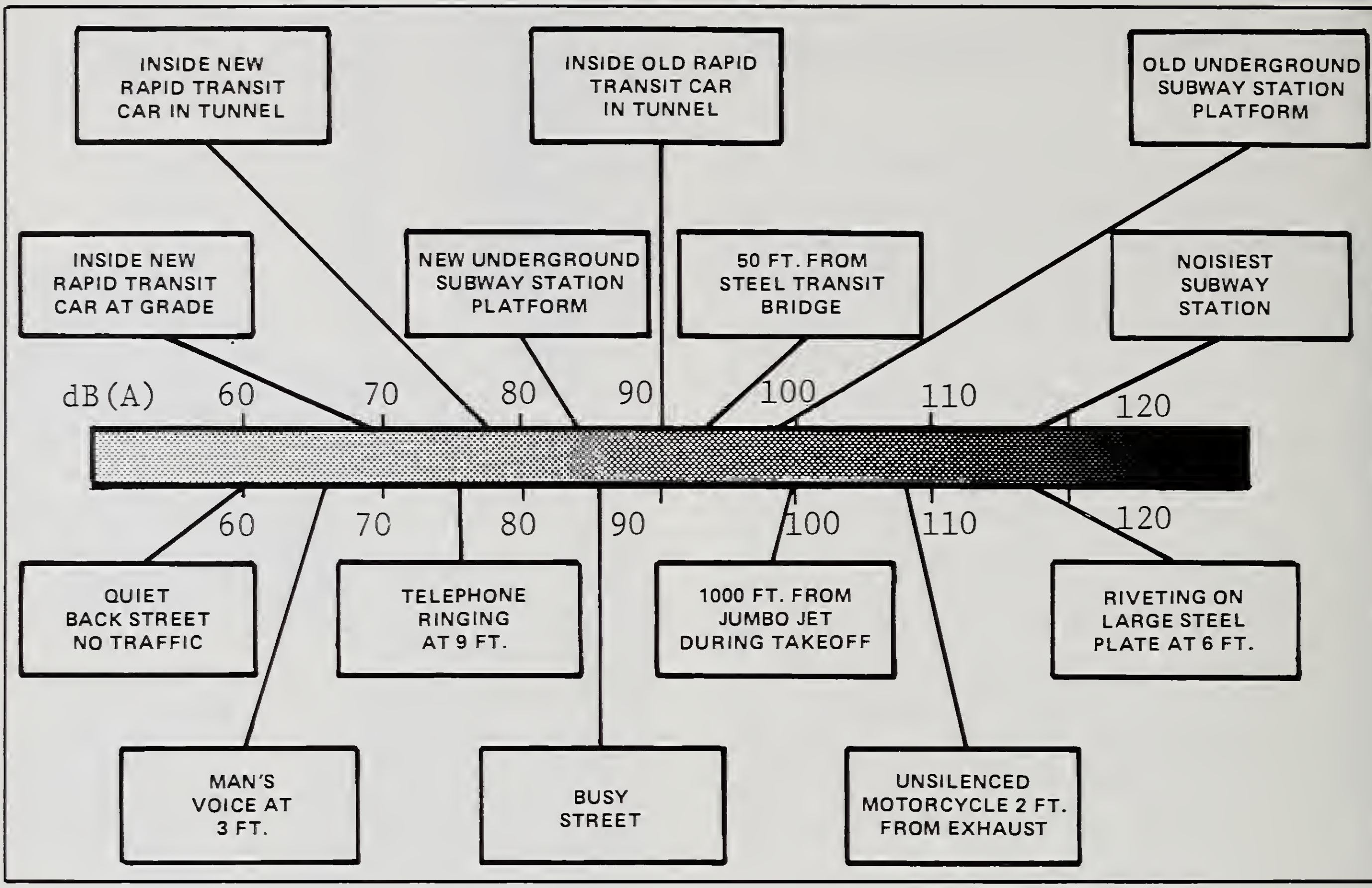


Figure 2. Typical Noise Levels in dBA

nated from), path (how the noise was transmitted), and receiver (where the person hearing the noise was located). The primary categorization was in terms of the receiver. *In-car noise* is heard by persons who are riding in transit cars; *in-station noise* is heard by persons waiting in stations; and *wayside noise* affects persons living or working in areas adjacent to transit lines. The noise in each of the above categories may originate from one or more sources and travels away from the source along various paths. Figures 3, 4, and 5 illustrate the paths noise follows in each of the noise categories.

For assessment purposes, transit systems were divided into segments according to various system characteristics, such as station type, vehicle type, trackbed type, and community location. Measurement of noise levels at all points along the system was not practical. The selection of measurement locations representing typical combinations of system characteristics allowed the extrapolation of measured noise levels to the entire system. In addition to surveying general noise levels, noise anomalies, such as squeal noise on curves, air brake release noise, and mechanical door operation noise were systematically measured.

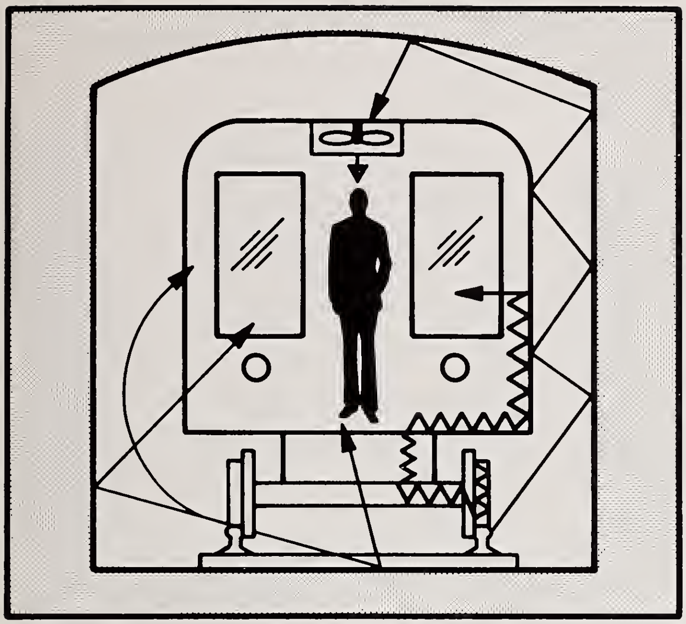
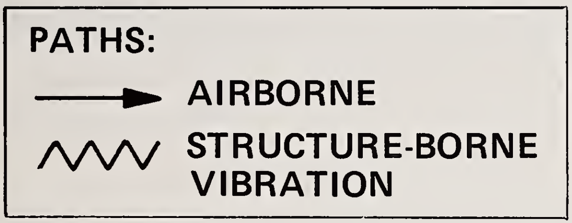


Figure 3. In-Car Noise Sources and Paths



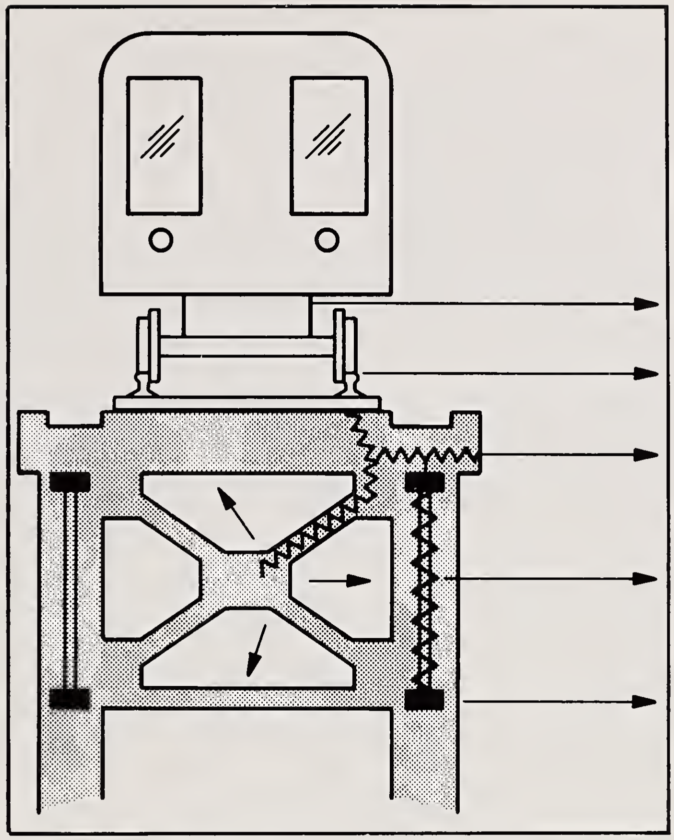


Figure 5. Wayside Noise Sources and Paths

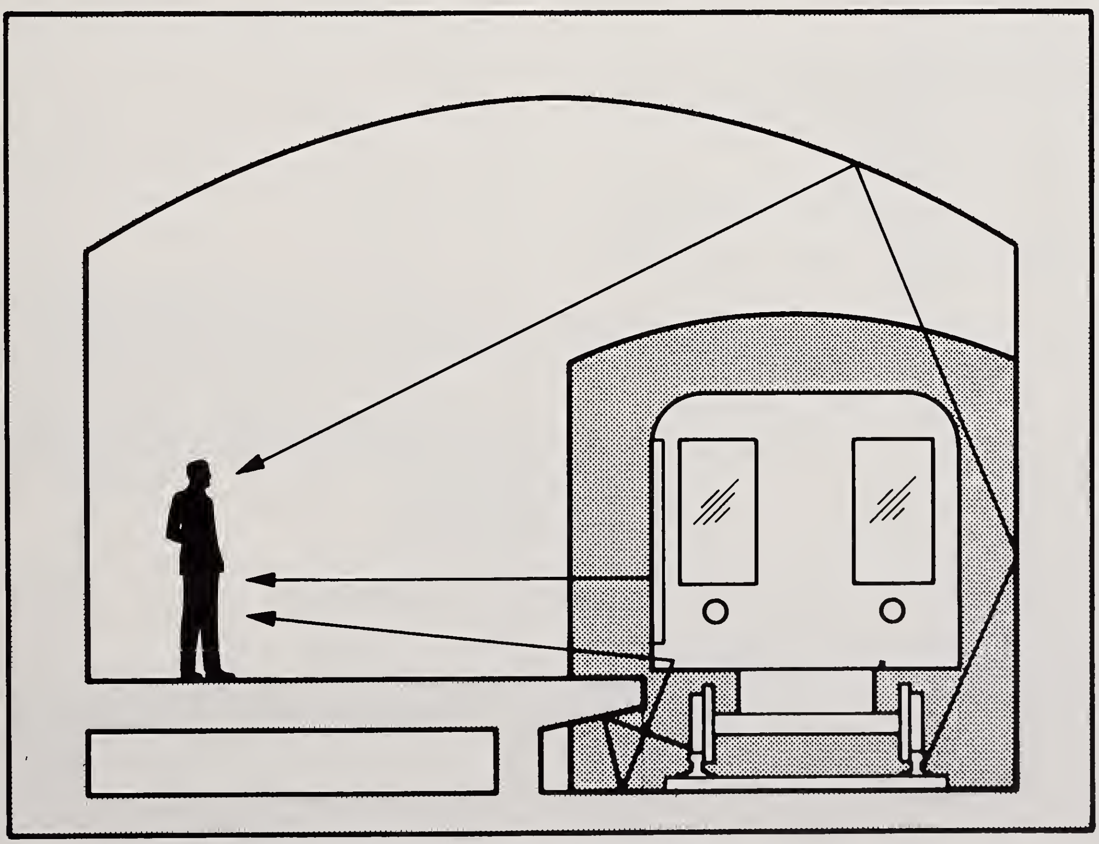


Figure 4. In-Station Noise Sources and Paths

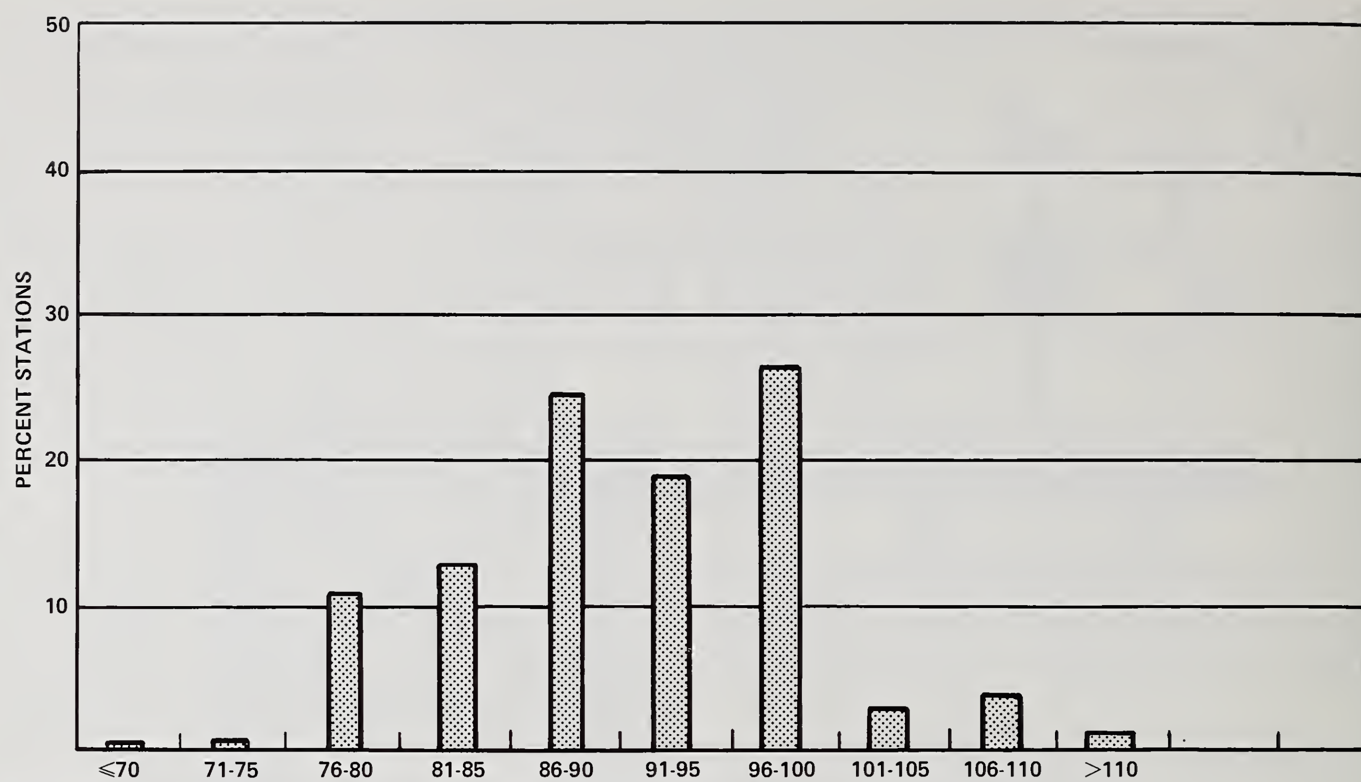


Figure 6. Maximum Noise Levels in Transit Stations Nationwide (in dBA)

Assessment Results

Results of the individual system assessments (12-18) were summarized into a national assessment report. (10) Data on noise levels was aggregated for in-car, in-station, and wayside noise. Figure 6 shows the aggregate distribution for in-station noise.

Certain system characteristics were found to be associated with higher noise levels. The location of track, i.e., underground, at grade, or elevated, was a principal determinant of noise level. Underground track typically produced higher in-car and in-station noise levels than aboveground track. Wayside noise levels associated with elevated track were typically higher than those associated with at grade track. Other conditions correlated with high noise levels included high train speed, jointed as opposed to continuous welded rail, flat spots on wheels, rough rail surfaces, and sharp curves in the track.

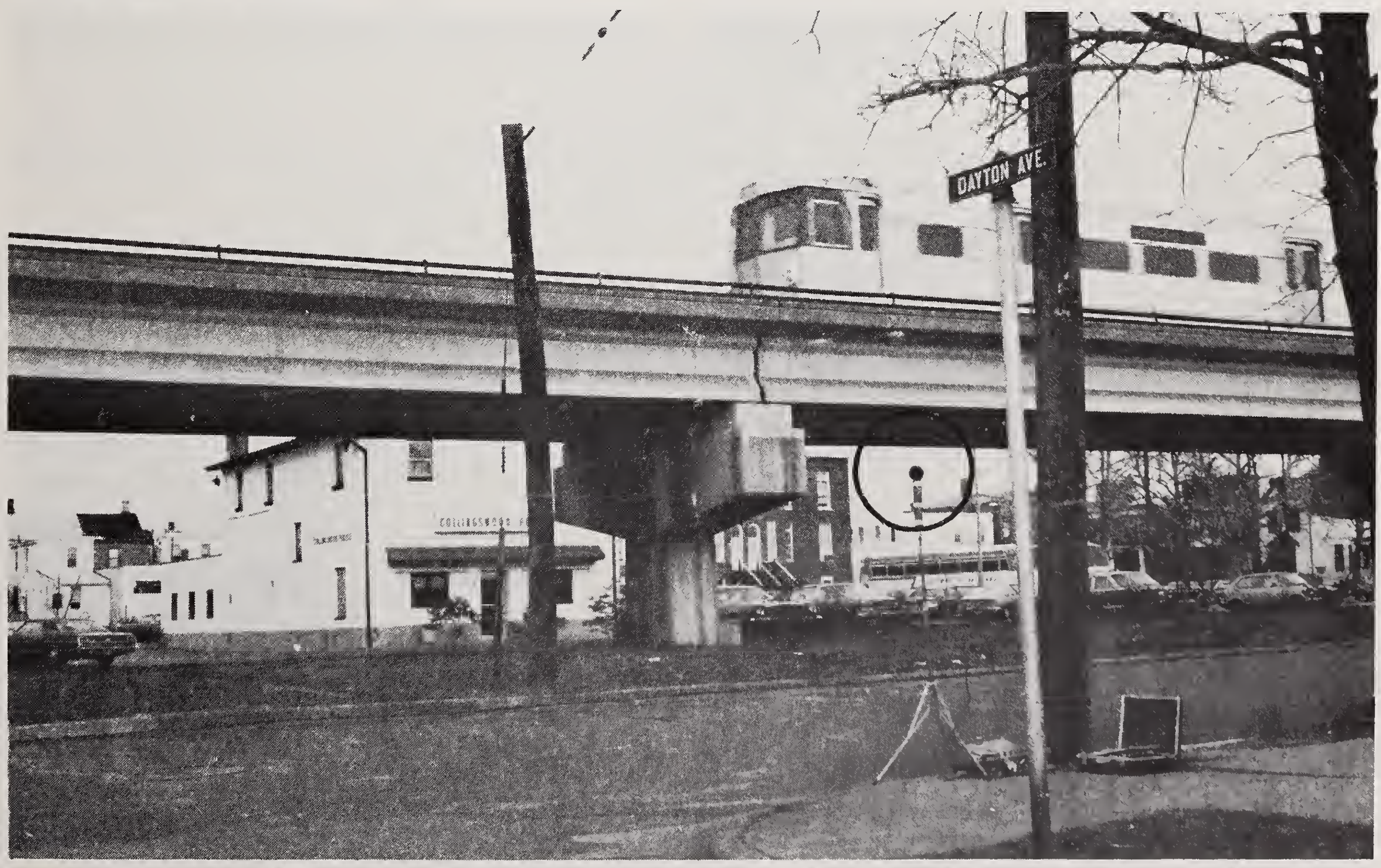
The age of the transit system was another determinant of noise levels. In-car noise levels were typically higher in older cars on underground sections of track, a condition prevalent on SEPTA, NYCTA, and CTA. New systems with acoustically treated cars and stations generally had lower in-car and in-station noise levels. Underground stations on the BART system which had been acoustically treated had lower noise levels than aboveground BART stations despite the fact that in general underground stations are noisier than aboveground stations. Wayside noise levels showed less variation between old and new systems and were more influenced by factors such as train speed and wheel/rail condition.

Comparison with APTA Guidelines

As part of the national assessment report, maximum noise levels on each of the nine transit systems were compared with the noise level guidelines established by the American Public Transit Association (APTA). These guidelines

Microphones placed in stations measure sounds of arriving and departing trains as part of the assessment program.

Noise levels of moving trains are measured at specified distances from the track on each of the nine transit systems studied.



represent the transit industry's own view of what is desirable and practicable in the control of rail transit noise. The guidelines are designed to insure that private conversations can be carried on in normal voices. At background noise levels of 78 dBA, people who are one foot apart can communicate in normal voices, but at 83 dBA, they must raise their voices in order to be heard.

The APTA guidelines specify acceptable maximum in-car noise levels from 70 to 80 dBA and in-station noise levels from 75 to 85 dBA, varying according to track structure type. For underground track, noise level goals were set higher because it is not practicable to reduce noise levels to the same degree as for aboveground track. Wayside noise level goals vary in relation to the type of buildings and land use in the wayside community. These goals range from 70 dBA for residential areas to 85 dBA for industrial areas.

In most cases, the noise levels reported in the national assessment exceeded those cited in the APTA guidelines. In-car noise levels were above those cited in the APTA guidelines for approximately 90 percent of the total route mileage covered. In-station noise levels exceeded APTA guidelines for approxmately 95 percent of the total route mileage covered.

Cost-Effectiveness Studies

Following completion of the eight assessments, studies on the cost and effectiveness of various noise abatement treatments were done on the same transit systems. (13, 23, 34) The methodology developed to estimate costs of noise reduction for the MBTA served as a model for the other systems. Estimates were made of the effectiveness of known abatement treatments and the cost of applying treatments to specific sources and paths. This information was incorporated into a computer program which calculated the minimum cost to reduce noise to various specific dBA levels, for example to 70 dBA, 80 dBA, or 90 dBA. Cost estimates were done for in-car, in-station, and wayside noise. Included in the estimates was the cost of eliminating noise anomalies such as wheel squeal, as well as the reduction of general noise levels.

These studies, along with a revised study of cost-effectiveness on the NYCTA, form the basis for on-going work on noise abatement cost-effectiveness. (12) Under the technology deployment program area, a computer program package is being developed known as PEACE (Computerized Procedure for the Evaluation of Abatement Cost-Effectiveness). This program will serve as a tool for transit managers and others involved in noise control planning, allowing them to select that combination of noise abatement techniques which will reduce overall noise levels most cost-effectively or to compare alternative noise control strategies.

2. Technology Development and Evaluation

Four types of urban rail noise constitute the most severe problems: wheel/rail noise, elevated structure noise, groundborne noise, and propulsion system noise. In this chapter technology development and evaluation activities are described for each of these categories of noise.

Wheel/Rail Noise

The sounds made by the interaction of steel wheels on steel rails is a major contributor to the urban rail transit noise problem. A major research effort has been undertaken by UMTA to develop a better understanding of the mechanisms involved in wheel/rail noise production. The effort involves the development of analytic models to predict wheel/rail noise, the testing of model predictions against laboratory and field measurements, and the use of these findings to improve the effectiveness of wheel/rail noise abatement treatments. (31, 32, 33)

Development of Analytic Models for Wheel/Rail Noise

Wheel/rail noise falls into three broad categories, each produced by a different mechanism: squeal, impact, and roar. Squeal (or screech) is the high-pitched noise produced as a train rounds a sharp curve. Impact noise is the "clickety-clack" or banging sound heard as the train travels along the track. Roar is a steady sound produced continually by wheel/rail interaction.

All wheel/rail noise is generated by the interaction of wheel and rail. This interaction produces a force at the point where the wheel and rail meet which causes both to be set into vibratory motion, and, in turn, to radiate sound waves outward. Figure 7 is a schematic representation of the noise generation process for wheel/rail noise.

The first analytic models developed by UMTA were for the processes of vibratory response and sound radiation of the wheel and rail since these processes are fundamental to

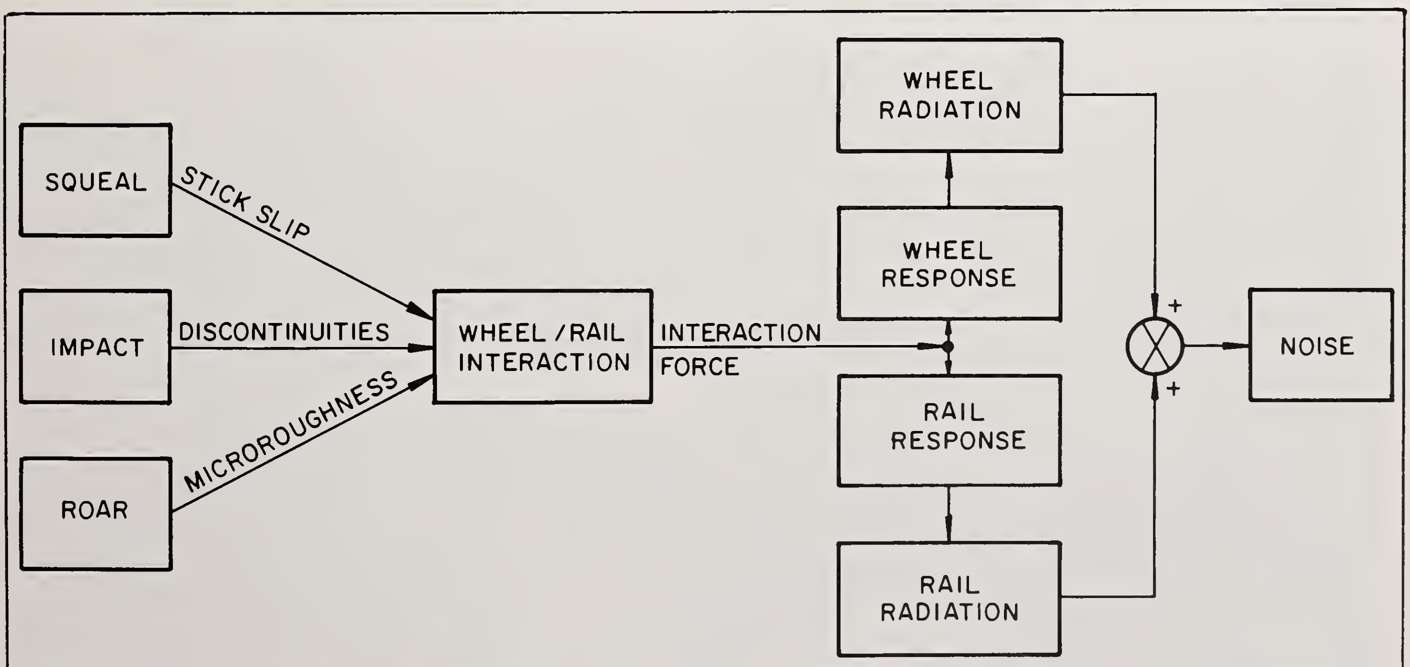


Figure 7. Wheel/Rail Noise Generation Process

wheel/rail noise generation. The models were tested in a series of laboratory experiments which employed an electromagnetic shaker to simulate wheel/rail interactions.

Following this, analytic models were developed for the mechanisms producing squeal, impact, and roar noise. These models were verified through both laboratory and field tests. A 1:8 scale model of a transit car undercarriage was used in the laboratory testing. The field tests employed a small 4-to-6 passenger personal rapid transit (PRT) vehicle with steel wheels running on steel track.

The test results in combination with existing knowledge produced a better understanding of the mechanisms involved in the production of squeal, impact, and roar noise.

Squeal noise appears to be produced in the following manner. A typical transit car is supported on two 2-axle trucks. The axles are rigidly attached to the truck making it difficult for the wheels to conform to the geometry of the rail on sharp curves. When rounding curves, the wheels do not roll continuously along the rail, but must slide laterally a certain amount. The

Experiments performed with this test vehicle were used to verify wheel/rail noise models.

Train squeals rounding sharp curve on elevated section of track.

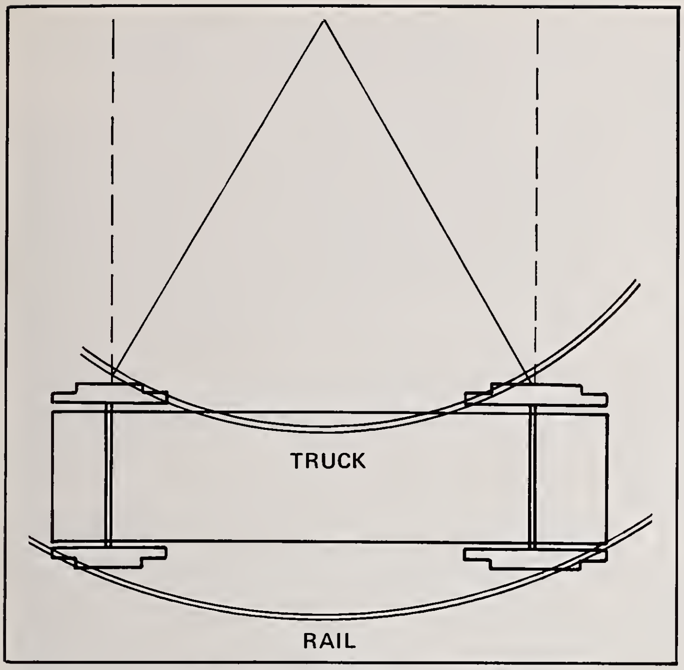


Figure 8. Squeal Noise Generation

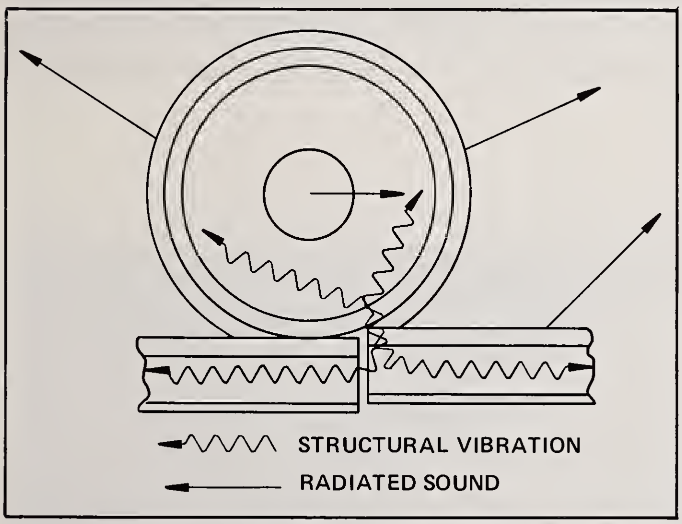


Figure 9. Impact Noise Generation

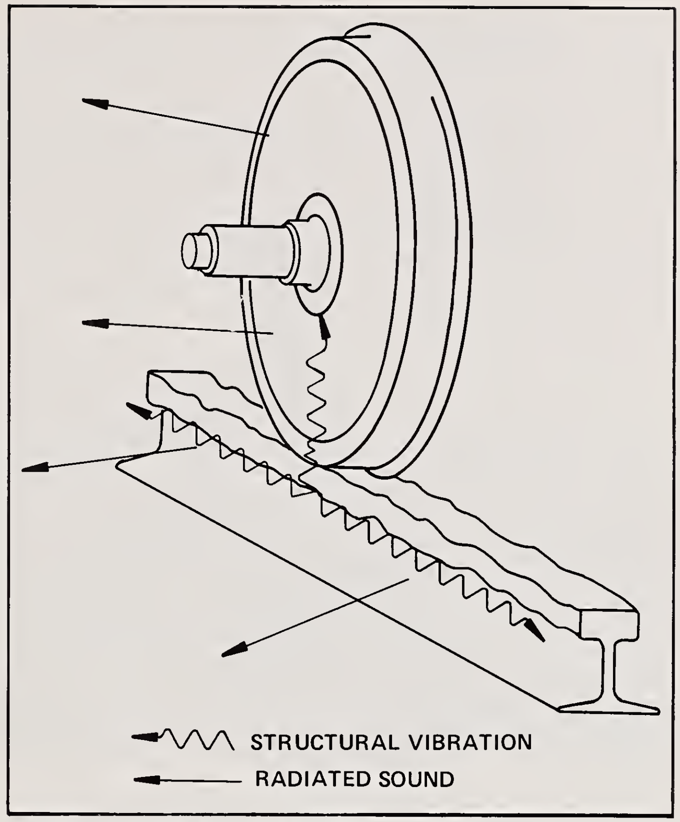


Figure 10. Roar Noise Generation

result is an alternate sticking and slipping motion along the rail known as "crabbing." This imperfect orientation of the wheels to the rail, illustrated in Figure 8, allows the "stick-slip" motion to begin. It is this "stick-slip" coupled with the vibratory response of the wheel that produces a high pitched squeal. The most prominent factors influencing squeal noise are the ratio of the radius of the curve to the length of the truck wheelbase, the vibration damping characteristics of the wheels, and the degree of adhesion between wheel and rail surfaces.

Impact noise is produced by discontinuities in the surfaces of the wheel or the rail. These discontinuities consist primarily of uneven rail joints and of worn areas on the rim of the wheel known as "wheel flats." Wheel flats are produced by locking of wheels during braking. Findings indicate that if both rail ends are at the same height, impact noise is negligible. If the first rail end (i.e. the rail on which the train is approaching) is higher than the second rail end ("step-down joint"), the noise level increases with speed up to a point beyond which it remains constant. When the first rail end is lower than the second rail end ("step-up joint") as illustrated in Figure 9, then the noise level increases constantly with train speed. Thus step-up joints represent a more serious noise problem. Noise due to wheel flats behaves in a manner similar to step-down joint noise — above a certain speed noise levels do not increase.

Roar noise is due to small-scale roughness on the surface of wheels and rails as illustrated in Figure 10. According to research results, the larger the contact patch (area in which the wheel and rail are in contact), the less roar noise is generated. Another finding indicates that at frequencies where roar noise peaks, the rail predominates over the wheel as the radiator of noise.

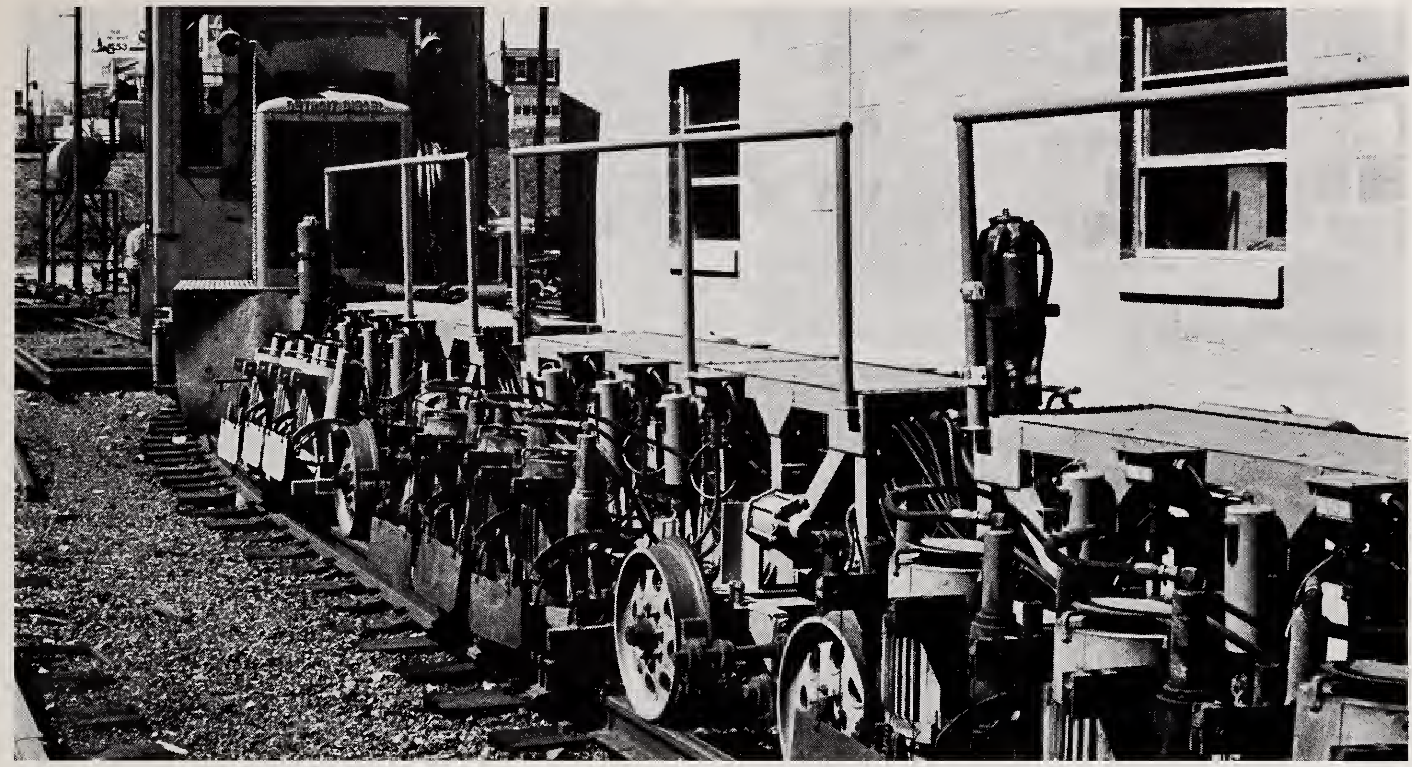
Based on the increased understanding of wheel/rail noise-generating mechanisms obtained through model development and validation, the following ways to abate wheel/rail noise suggested themselves. Although valid in theory, not all of these methods are equally practical for application on transit systems.

Squeal noise may be reduced by preventing the stick-slip mechanism or by lessening the vibrations produced by it. Trucks with shorter wheelbases or articulated trucks (i.e. trucks which pivot in the center allowing axles to conform to curves) may prevent crabbing and hence stick-slip. Lubrication of the wheel and rail can prevent the stick-slip mechanism from being activated. Finally various damping devices applied to the wheel can reduce squeal by suppressing the vibrations created by the stick-slip mechanism.

Impact noise generated by rail discontinuities may be eliminated by the use of welded rail (elimination of rail joints) or through routine maintenance to keep rail joints in proper alignment. The contouring of the second rail end may also help reduce impact at rail joints. Impact noise due to wheel flats can be prevented by routine inspection of wheels and subsequent truing (machining) of damaged wheels. The use of resilient wheels (i.e. wheels with resilient material between the tread and hub) may reduce impact noise by lessening vibrations transmitted into the wheel from the point of impact.

Roar noise can be reduced through routine grinding of rails (machining of rail surfaces) and truing of wheels. Other techniques, such as resiliently treaded wheels (i.e. wheels with a layer of resilient material on the tread covered with a thin layer of steel) could possibly reduce roar noise by creating a larger contact patch between the wheel and rail, but need further investigation.

Wheel flats are one cause of impact noise.



SPENO grinding train removes rail roughness by lowering abrasive wheels onto the rail surface.

SEPTA Wheel/Rail In-Service Test Program

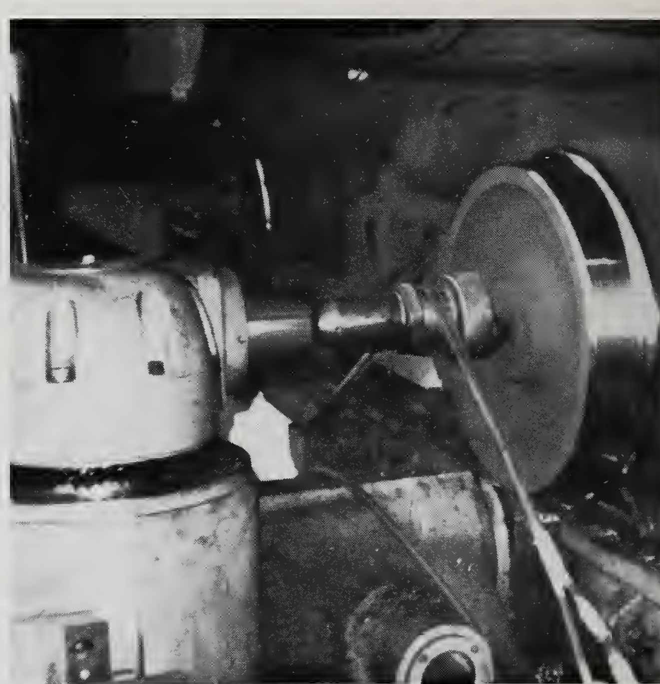
In order to evaluate the acoustical effectiveness, durability, and costs of various wheel/rail noise control techniques, UMTA undertook an in-service testing project on the SEPTA system (4-8). Included in the testing were (1) resilient wheels (wheels manufactured with a resilient material between the tire and hub that acts to damp vibration), (2) damped wheels (standard wheels retrofitted with a damping device to reduce vibrations), (3) wheel truing (machining wheel tire surfaces to remove irregularities created during train operations), (4) rail grinding (grinding of rail running surfaces to remove roughness created by train operations), and (5) the use of welded rails (welding rail ends together in order to eliminate the impact which occurs at rail joints) were evaluated as a noise control treatment.

During the in-service testing noise and vibration measurements were made for a number of different combinations of train speeds, track structures, and rail types. Wheel truing and rail grinding were evaluated by comparing the performance of factory new wheels, recently-trued wheels, and worn wheels, and of recently-ground rail and worn rail. Following the first round of testing, wheels and rails were allowed to wear naturally during a year of in-service operations to determine how well they held up over time. After the year of wear, the various noise abatement techniques were retested.

Three types of resilient wheels were tested — the Acousta Flex wheel, the Penn Cushion (Bochum) wheel, and the SAB wheel. These wheels are illustrated in Figure 11. During the course of the testing, each type of resilient wheel developed some form of operational difficulty and had to be withdrawn from the study. The SAB and Bochum wheels sustained damage due to overheating caused by the application at high speeds of the tread braking system, used on SEPTA as a backup to the regular dynamic braking system. These problems raise questions about the compatibility of resilient wheels with tread braking systems although the two have been used together successfully on other transit systems. On the Acousta Flex wheel, a bonding failure occurred between the resilient material and the rim caused by incomplete bonding during manufacture.

The damped wheels initially scheduled for testing were considered unsatisfactory and were not included. In their place, "ring-damped" wheels were tested. These are standard wheels with a groove cut on the inside of the tread and a metal ring snapped into the groove. The ring, although restrained by the groove, is free to move within it and acts to damp vibration.

In addition to the acoustic measurements, vibration levels were measured to determine if the wheel/rail noise abatement techniques were also effective in reducing vibration. Measurements were taken along welded track test sections in the subway and on elevated structure, for trains with worn and trued wheels and for trains with each of the three types of resilient wheels. Tests were performed both before and



An underfloor milling machine is used for wheel truing operations on SEPTA.

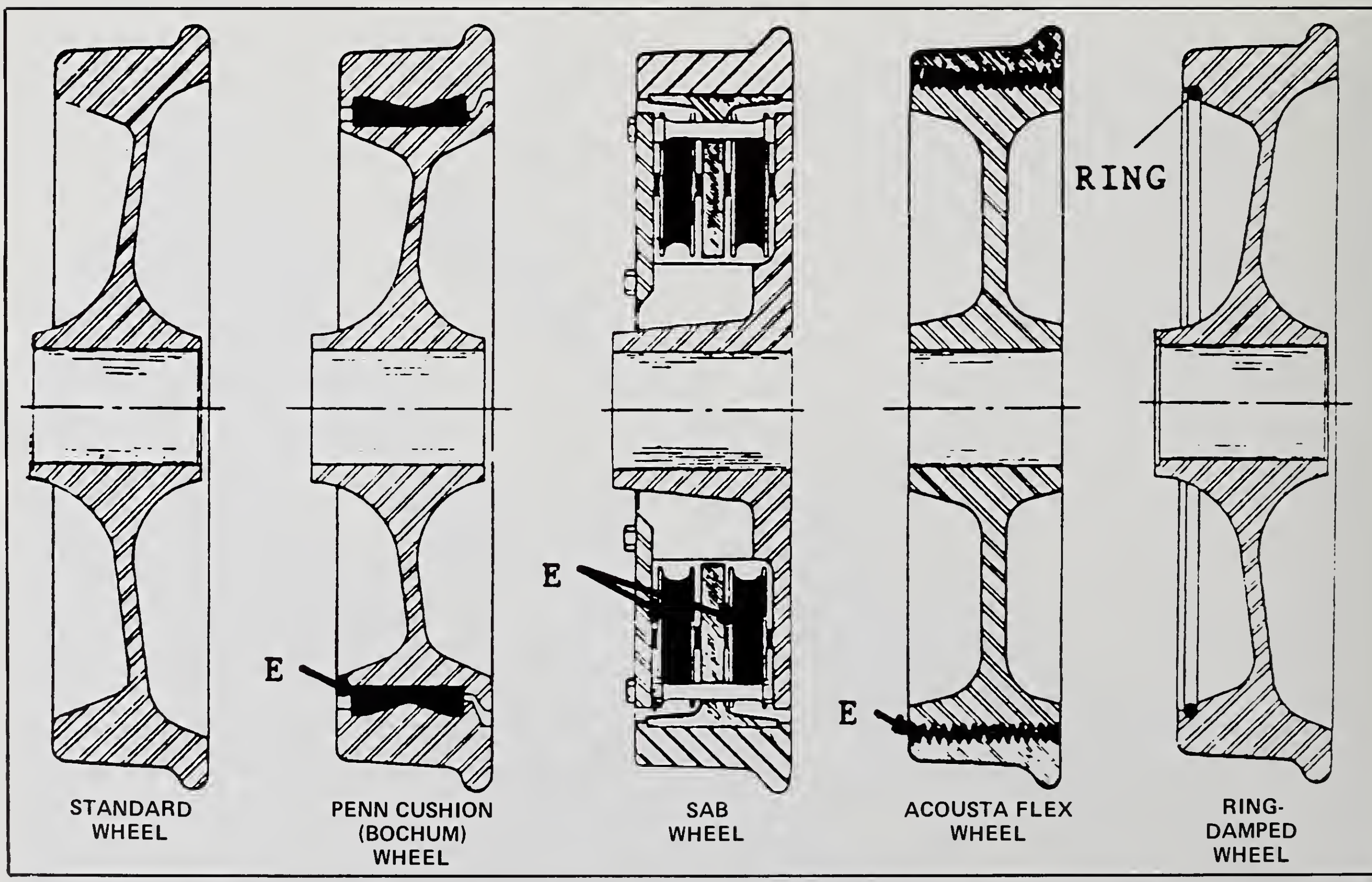


Figure 11. Standard, Resilient, and Ring-Damped Wheels Tested at SEPTA. (E indicates the Location of Elastomeric Material on the Resilient Wheels).

after rail grinding. (A discussion of groundborne and structureborne vibration is contained in upcoming sections of this document.)

Measurements were also taken of the noise generated by the train's propulsion system. If noise from this source is high enough, it can mask reductions in wheel/rail noise produced by the abatement treatments. To gauge the importance of propulsion system noise on SEPTA, a transit car was raised above the track, and noise measurements were taken with the propulsion system running. (A discussion of propulsion system noise is contained in an upcoming section.)

Results of In-Service Testing at SEPTA

Some significant reductions in wheel/rail noise were observed during the SEPTA in-service testing. Resilient wheels and ring-damped wheels were found to produce large reductions in wheel squeal noise on curved sections of track. In certain cases, squeal noise was eliminated completely. Typical reductions were on the order of 10 dBA, but the perceived decrease in noise was even greater due to the annoying character of squeal noise.

Welded rail was found to be a significant improvement over jointed rail with an average noise reduction of 4 dBA in the wayside community. Again the subjective impression of reduction was greater than indicated by the dBA reduction because of the annoying character of impact noise.

Except for the above-mentioned findings, noise reductions achieved were not dramatic and typically were not enough to make a noticeable difference in transit cars or in the surrounding community. Although effective on curved track, resilient wheels and ring-damped wheels did not produce noteworthy reductions on tangent (straight) track. Also, since wheel flats and rail corrugations were not noticeably present on the SEPTA system, wheel truing and rail grinding were not particularly effective. Another factor was the level of propulsion system noise. In general propulsion system noise was comparable in magnitude to wheel/rail noise on the SEPTA system, and thus limited the reduction in wheel/rail noise that could be observed. In order to produce dramatic reductions in noise levels on SEPTA, both propulsion system noise and wheel/rail noise must be abated simultaneously.

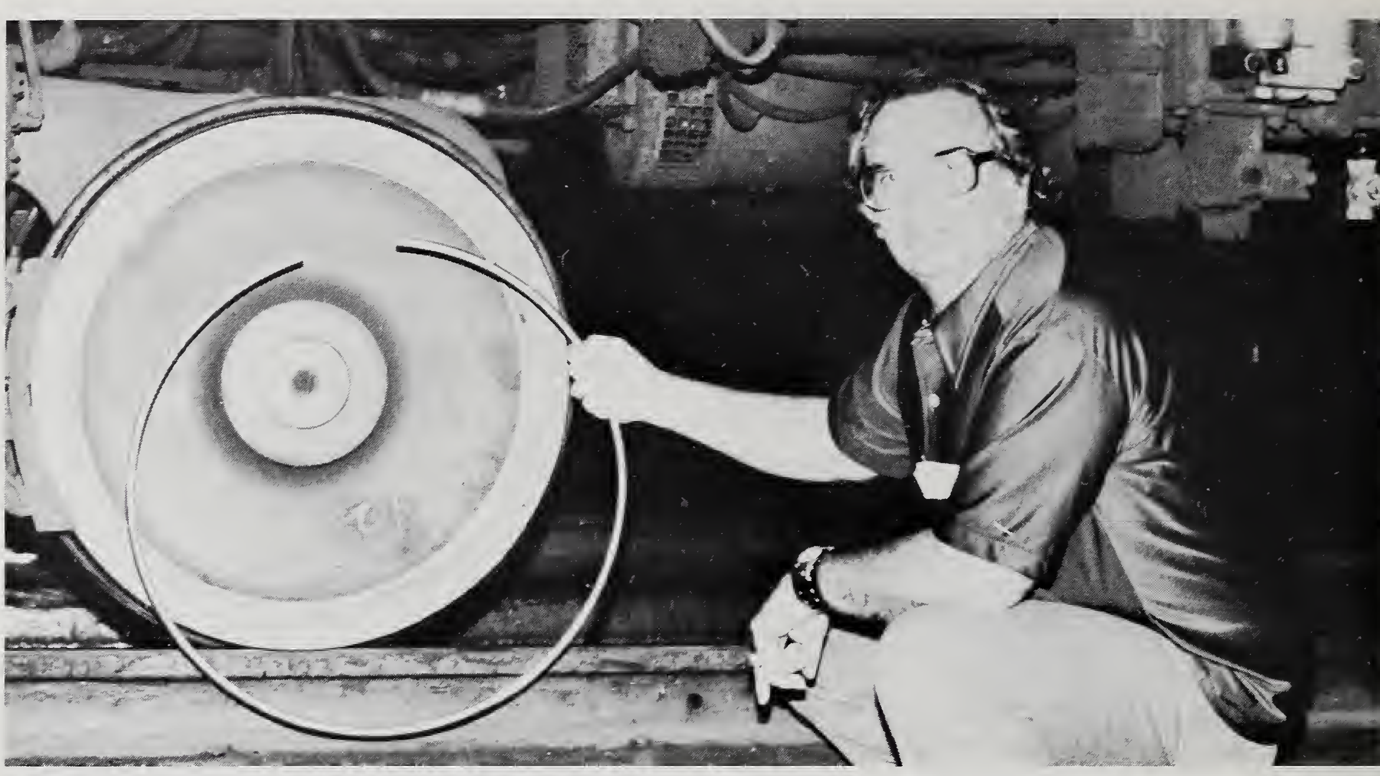
Vibration levels measured on SEPTA were found to be significantly reduced by the use of resilient wheels. Wheel truing and rail grinding did not produce significant vibration reductions on SEPTA although data from other systems suggests that these techniques are effective when noticeable wheel flats and rail corrugation are present on a system.

As mentioned above, resilient wheels tested developed problems during operation and may not be compatible with the use of tread braking. The ring-damped wheels also developed operational difficulties during the course of the study. Over a 10-month period, the rings "froze" in the grooves eliminating any abatement effectiveness. This situation has not arisen with ring-damped wheels in use on other systems, for example in Chicago and in London where they have been used without problems. It appears that corrosion or accumulated brake dust may be responsible for the adherence of the rings in the grooves. Further investigation of the problem is called for.

Further Work on Wheel/Rail Noise Abatement Techniques

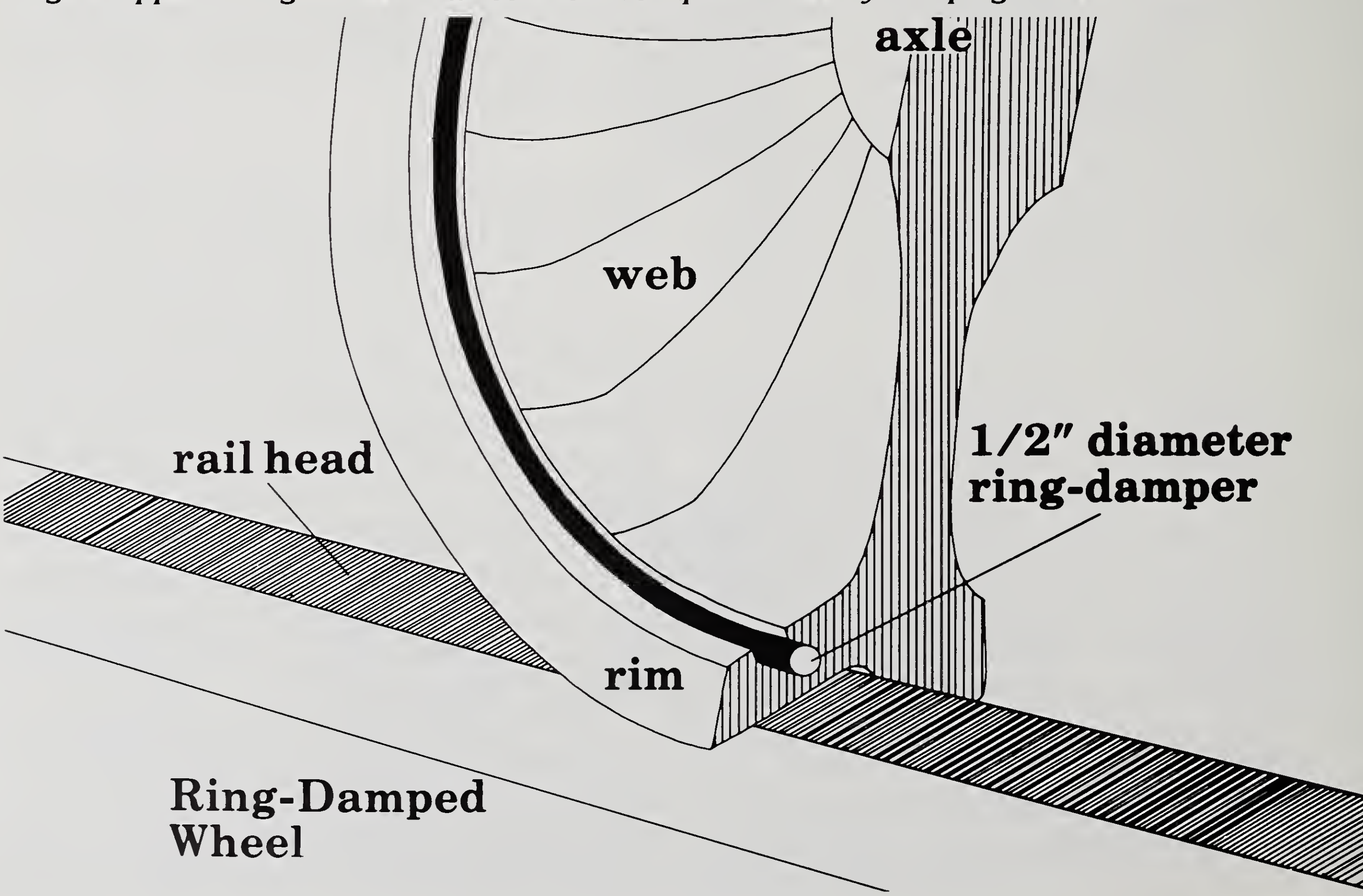
Work on improving the effectiveness of wheel/rail noise abatement treatments is being continued. Previously developed mathematical models of wheel/rail interaction will be refined based on the collection of new data and on field tests. The testing will be performed at the Pullman Standard test track in Champ Ferry, Indiana and at the Department of Transportation's Transportation Test Track in Pueblo, Colorado, and at several transit systems, including NYCTA, MBTA, and CTA.

For selected wheel/rail noise abatement treatments, the improved models will be used to optimize the design parameters of the treatments, i.e. the models will be used to predict which design changes will produce maximum



Vibration-damping rings are placed in grooves cut in the rim of the wheel.

Rings snapped into grooves on wheels reduce squeal noise by damping wheel vibration.



Noise levels for trains operated on elevated structures can be as much as 20 dBA higher than for trains operated at grade.

reductions in noise levels. Once designs have been optimized in this way, actual hardware will be obtained or manufactured, and will undergo field testing. The most successful treatments will then be selected for in-service testing on transit systems.

Elevated Structure Noise

When a train travels over an elevated structure, vibrations created by wheel/rail interaction are transmitted through the track to the supporting structure. The vibrating structure radiates noise to surrounding areas, increasing noise levels significantly over those produced by trains running on at grade track. Elevated structure noise levels can be as much as 20 dBA higher than those for at grade train operations.

Noise from elevated structures is a significant problem on U.S. transit systems; 30 percent of all urban transit route mileage is on elevated structures. Along much of this distance, the wayside community is within 50 feet of the track and experiences noise levels in excess of 90 dBA. In New York City alone, there are 70 route miles of elevated structure. Current technology does not appear adequate for reducing the noise levels near elevated structures on the New York City system to 85 dBA. More effective ways of reducing noise in communities near elevated transit lines are needed.

Development of Analytic Models for Elevated Structure Noise

During the initial stages of the program, a review was conducted of existing knowledge on the prediction and control of urban rail noise and vibration. (24) The focus of the review was on the paths along which noise and vibration propagate as they travel outward from the source rather than on the generation of noise at the source. Two areas treated in the review were selected for further study, elevated structure noise and vibration and groundborne noise and vibration from tunnels.

With regard to elevated structure noise and vibration, the review found prediction techniques inadequate. Correlations existed between noise levels and general types of elevated structures; for example steel elevated structures were typically noisier than concrete elevated structures. However, it was not possible to predict the noise radiated by individual structural elements. This more detailed knowledge was needed in order to estimate noise levels produced by new elevated structure designs and by design modifications made on existing structures for noise abatement purposes.

To this end, mathematical models of elevated structure noise have been developed. (21) Three different types of elevated structures were modeled, including concrete deck on steel plate girders, open tie deck on steel plate girders, and open tie deck on open web steel girders. These models were tested against field measurements on Boston's MBTA for the three types of elevated structures. The test results partially validated the accuracy of the models.

One of the significant findings of this research was that rails are the dominant noise source at high frequencies, while steel girders dominate the mid-range frequencies. In order to significantly reduce the noise levels, noise from both rails and girders must be reduced.

Further Research on Elevated Structure Noise

A new research effort on elevated structure noise is underway. Tasks include the review of noise rating criteria to select those appropriate for elevated structure noise, an inventory of elevated structures, development of more accurate mathematical models, and development of design guidelines for elevated structure noise control.

The review of noise rating criteria has already been accomplished. (22) The measure selected was L_{dn}, which represents the average A-weighted sound level over 24 hours with a weighting applied for nighttime noise. Additionally, a method was developed to allow measurement of noise impact over an entire community. The Fractional Impact Method accomplishes this by weighting sound levels by the population exposed and summing impacts on individual subareas.

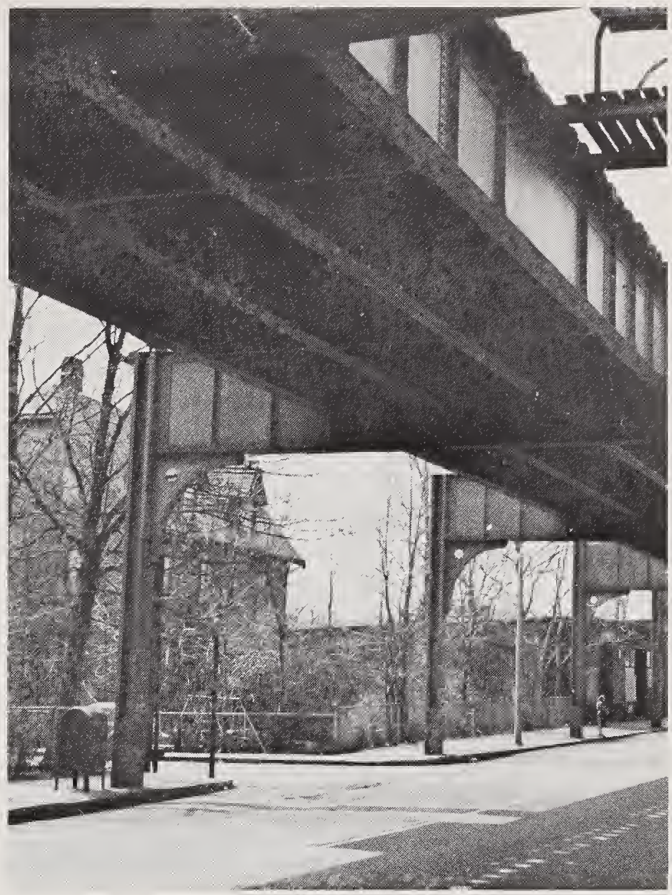
Present and planned U.S. elevated structures have been inventoried to identify the major types of structures, their length, the characteristics of these structures that contribute most directly to noise generation, typical noise levels associated with these structures, and the number of people impacted by the noise.

The models of elevated structure noise and vibration previously developed are being improved through extension and modification. For example, the model of wheel/rail interaction will be incorporated into the elevated structure model to improve prediction capability.

Using the improved analytical models and data from European, Japanese, and United States studies of elevated structure noise and noise control treatments, estimates will be made of the amount of noise reduction possible through the use of different treatments. This information will be summarized in design guidelines for each type of elevated structure, and presented in a form understandable to a nonspecialist. Potential sites will be selected around the United States that would be most appropriate for trial application of elevated structure noise control treatments.

Elevated Structure Noise Abatement Treatments

Based on research conducted to date, the following noise abatement techniques appear to



UMTA-sponsored research developed computer models to predict noise on three types of elevated structures — concrete deck on steel plate girder (left), open tie deck on steel plate girder (right), and open tie deck on open web girder (bottom).

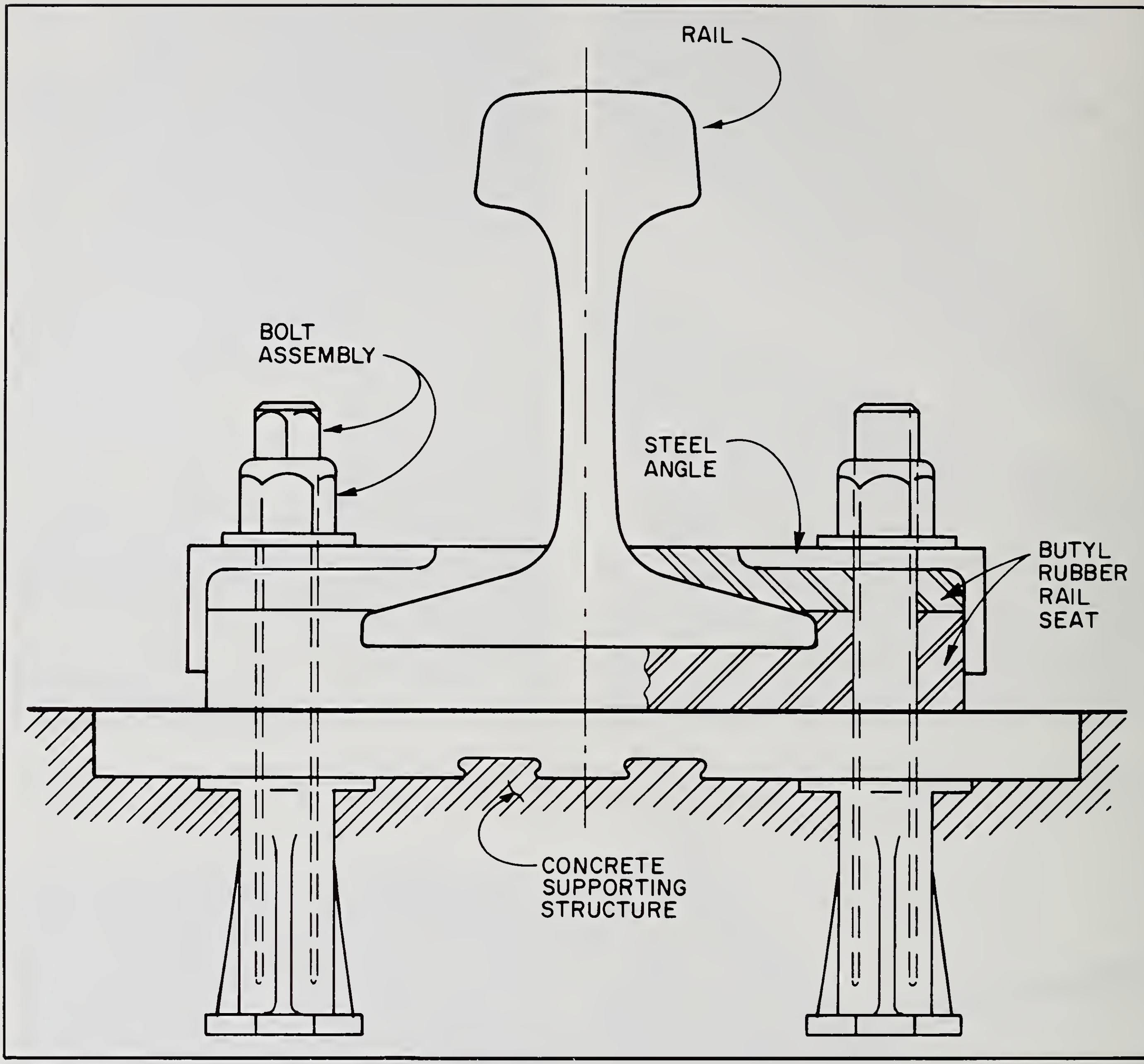


Figure 12. One type of resilient rail fastener

have the most promise for reducing elevated structure noise levels.

Since elevated structure noise is produced in part by the transmission of vibration to the structure, techniques which reduce rail vibration also reduce elevated structure vibration and noise. Rail grinding, wheel truing, and the use of welded rail instead of jointed rail all fall in this category. Rail grinding and welding may present safety and structural problems, however, which must be resolved.

Another strategy is to limit the amount of vibration that is transmitted to the structure. Resilient rail fasteners, which consist of pads of resilient material placed between the rail and the roadbed, reduce the transmission of vibration. One type of resilient rail fastener design is shown in Figure 12. The use of ballast, which consists of placing crushed rock between the track and roadbed, acts to absorb vibration and prevent its transmission to the elevated structure. The added weight, however, can create structural problems on older elevated structures. Moreover, most types of elevated structures are open deck and would have to be redesigned to carry ballast.

Shielding the elevated structure to prevent the radiation of noise into the wayside community is another abatement strategy. Barriers along the side of the tracks can reduce noise from the rails and enclosure of the sides and undersides of an elevated structure can block noise radiated from structural elements. Barriers and enclosures, however, may be prohibitively expensive.

While further analytical research on elevated structures is proceeding, various in-service tests of elevated structure noise control treatments are being carried out. One example is the recent test of resilient rail fasteners performed on elevated structures in New York City by the NYCTA. Butyl rubber pads were inserted between the rail and the wood ties. Noise measurements made before and after installation of the rubber pads revealed a varying reduction in the wayside noise from the track, depending on train speed. Figure 13 shows noise levels before and after installation of the resilient rail fastener treatment. The lack of noise reduction above 30 mph is believed to be because the propulsion system noise becomes dominant at higher speeds. Although this in-service testing was not a formal part of the Urban Rail Noise Abatement Program, the Transportation Systems Center did provide technical assistance for measurements and analysis.

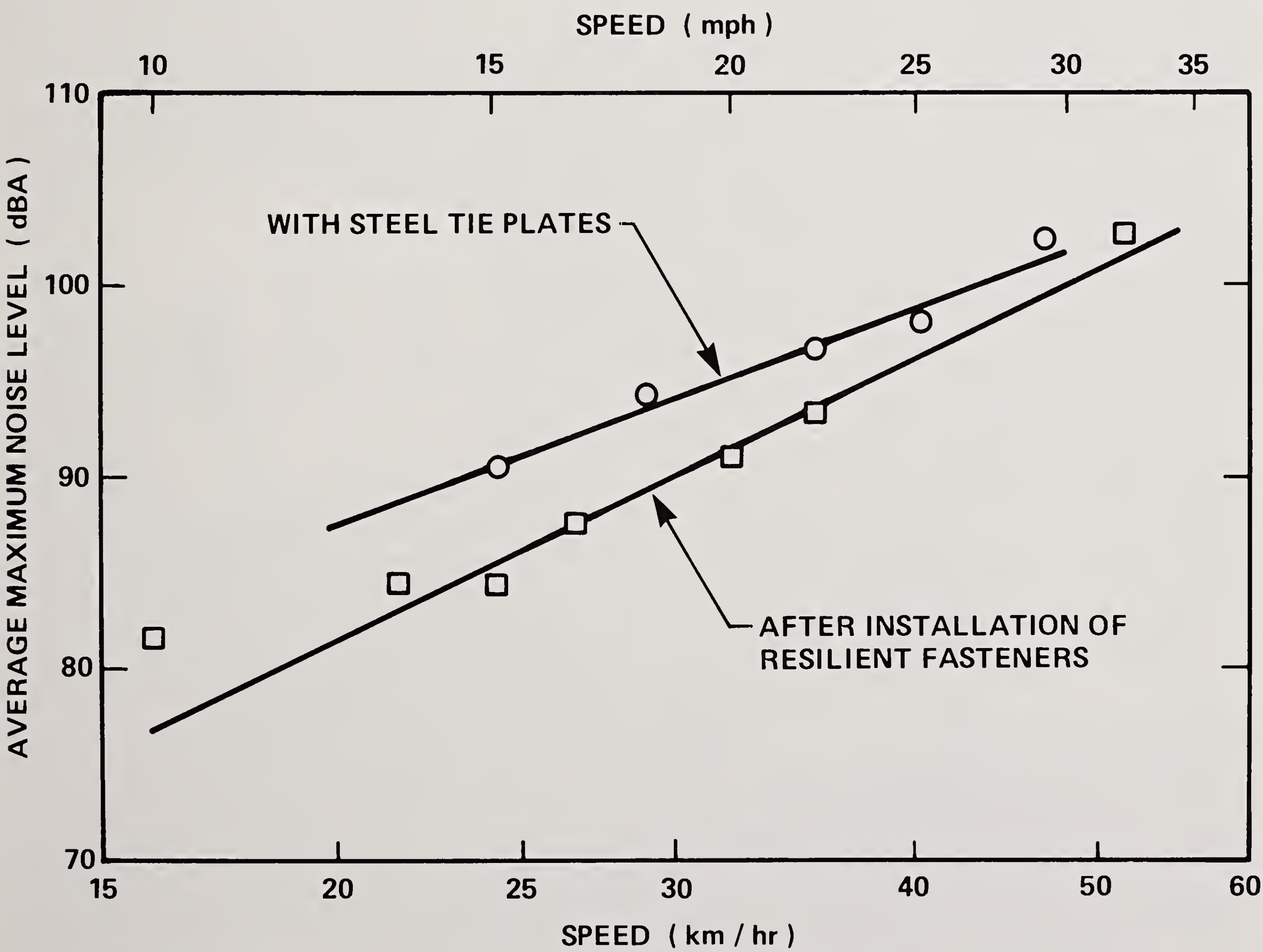


Figure 13. Effect of Resilient Fasteners on Wayside Noise at 25 feet from NYCTA Elevated Structure

Train operations cause surrounding buildings to vibrate.

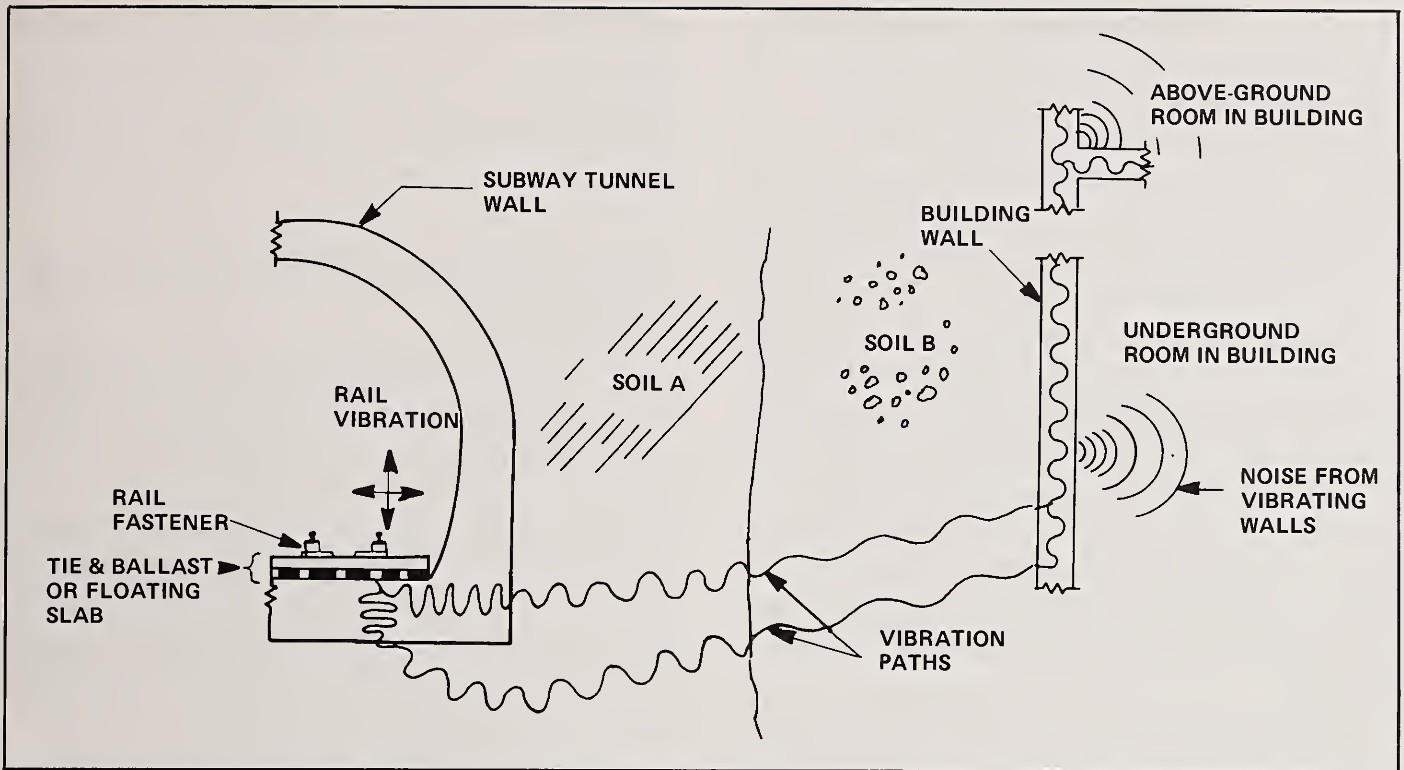


Figure 14. Schematic View of Propagation of Subway Vibrations into Buildings

Groundborne Noise From Subways

In underground portions of transit systems, vibrations generated by wheel/rail interactions are transmitted to the tunnel structure and then to the surrounding soil. The vibrations propagate through the soil to adjacent buildings, resulting in vibration of the floors and walls and secondary radiation of noise into the rooms. Figure 14 shows typical propagation paths of subway vibrations into buildings. Before the vibration levels are high enough to be felt, the secondary noise radiation due to a passing train can be heard as a low rumbling sound or as rattling sounds from objects in a room, such as windows or dishes.

Groundborne noise and vibration is a source of considerable annoyance, and a major source of community complaints received by transit authorities. It is one of the largest sources of complaints to the NYCTA. More cost-effective methods for prediction and control of groundborne noise and vibration are needed to alleviate this problem.

Development of Analytic Models for Groundborne Noise

The review of prediction and control techniques for urban rail transit noise and vibration, mentioned under the previous section on elevated structure noise, also provided the groundwork for subsequent research on groundborne noise and vibration. (24) The study found that current techniques for the prediction of groundborne noise and vibration were inadequate.

Research currently underway will attempt to improve noise and vibration prediction. A comprehensive mathematical model to predict the propagation of vibration from the subway structure to adjacent buildings is needed. In particular, the propagation of sound waves through the earth surrounding the tunnel requires further investigation. Researchers will draw upon the expertise of practitioners in the fields of rail transit noise and vibration control, geophysics, soil and rock mechanics and structural dynamics, including soil/structure interaction, to develop the model. Various analytic and empirical models have been developed already in relation to different aspects of the transmission of groundborne noise and vibration. The current project will refine and expand these models and will conduct further research to fill gaps in existing knowledge. The various models will be combined into an overall prediction model which will permit variations in the type of track (rail, rail fastening method, and trackbed), tunnel structure, surrounding earth, and building structure as a basis for prediction. Groundborne noise and vibration has been found to vary considerably from one transit system to another. Existing measurements of noise and vibration from the different systems will be collected into a data base which will be used to validate the prediction model, and to identify those factors which account for the variability between systems.

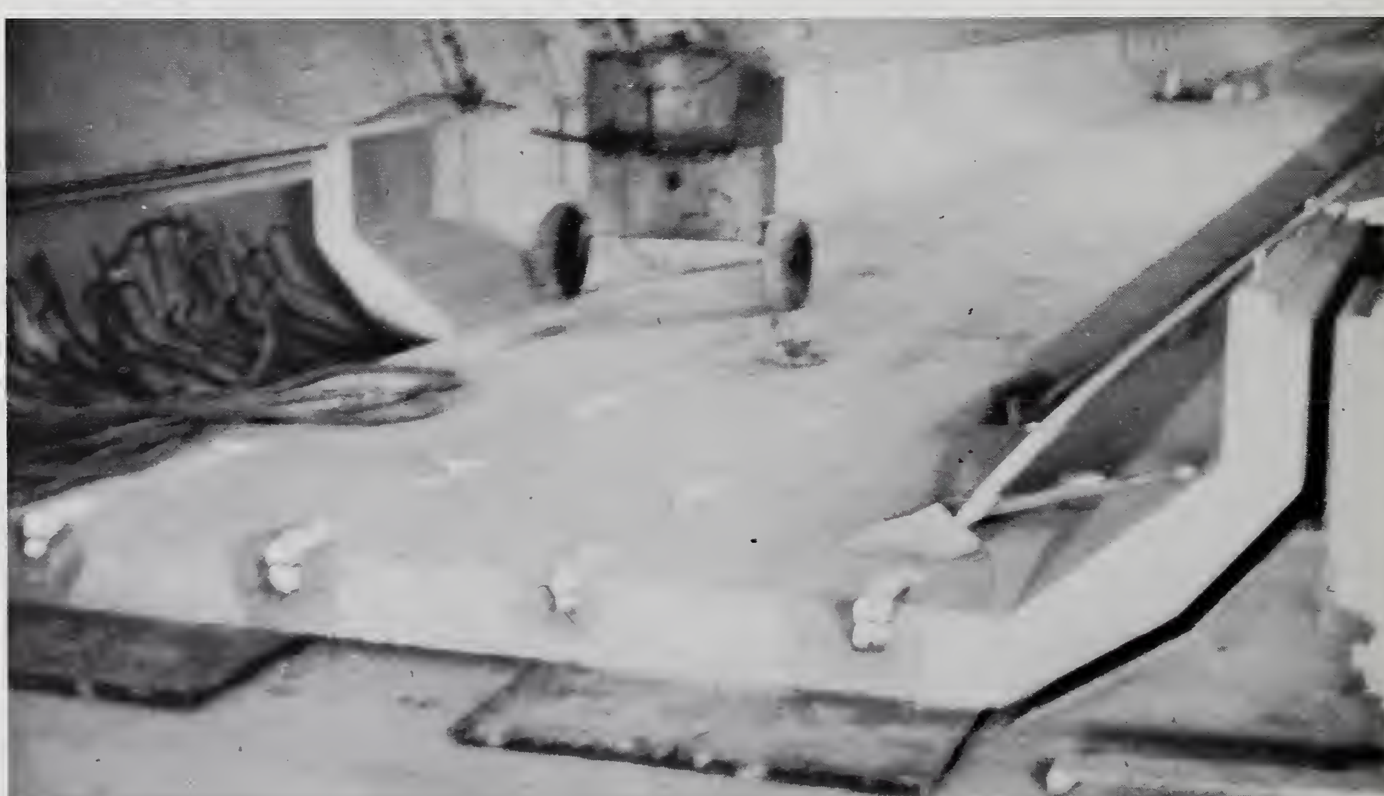
Groundborne noise and vibration control techniques will be surveyed and evaluated. The most promising techniques will be selected for further refinement. Using the prediction model, design modifications will be made in order to optimize the vibration control. Installation and maintenance costs, and the safety of the techniques will also be assessed. Finally, recommendations for in-service testing of the selected techniques will be made.

Groundborne Noise Abatement Treatments

Based on research done to date, the following techniques appear to be the most appropriate for reducing groundborne noise and vibration. As in the case of elevated structure vibration, any reduction in vibrations created during wheel/rail interaction will also lead to a reduction in vibration transmitted to the ground. Wheel truing, rail grinding, and the use of welded in place of jointed rail are all capable of reducing groundborne vibration in this way.

Another type of treatment acts to reduce the amount of vibration transmitted from the rails to the roadbed. Ballast, which consists of crushed rock placed between the track and the

Concrete floating slab trackbed supported on resilient pads reduce vibrations transmitted to the tunnel.



roadbed, acts in this way. Ballast can also reduce in-car noise levels in tunnels due to its absorptive properties. However, the use of ballast may require a larger tunnel diameter and hence not be feasible.

Resilient rail fasteners, which involve the placement of a resilient layer of material between track and roadbed, act to reduce the transmission of vibration. The "softer" or more resilient the fastener, however, the more likely it will produce track alignment or stability problems. Softer fasteners may also allow rails to vibrate more freely and possibly increase tunnel noise levels, while at the same time decreasing vibrations transmitted to the roadbed.

Resiliently mounted "floating slab" track beds appear to be a more effective technique for reducing vibration transmission. This method consists of rail mounted on concrete trackbed slabs isolated from the tunnel floor by resilient pads. Figure 14 shows a typical floating slab trackbed. Floating slabs are capable of reducing vibrations transmitted to the tunnel wall by 10 to 20 dBA over resilient fasteners or ballasted track. Disadvantages include the expense and the need for a larger tunnel in some cases.

Trenches dug along the sides of tunnel walls can act as a barrier preventing the transmission of vibration to adjacent buildings. However, there are practical drawbacks to this technique, in particular the need for very deep trenches to attain effective vibration reduction.

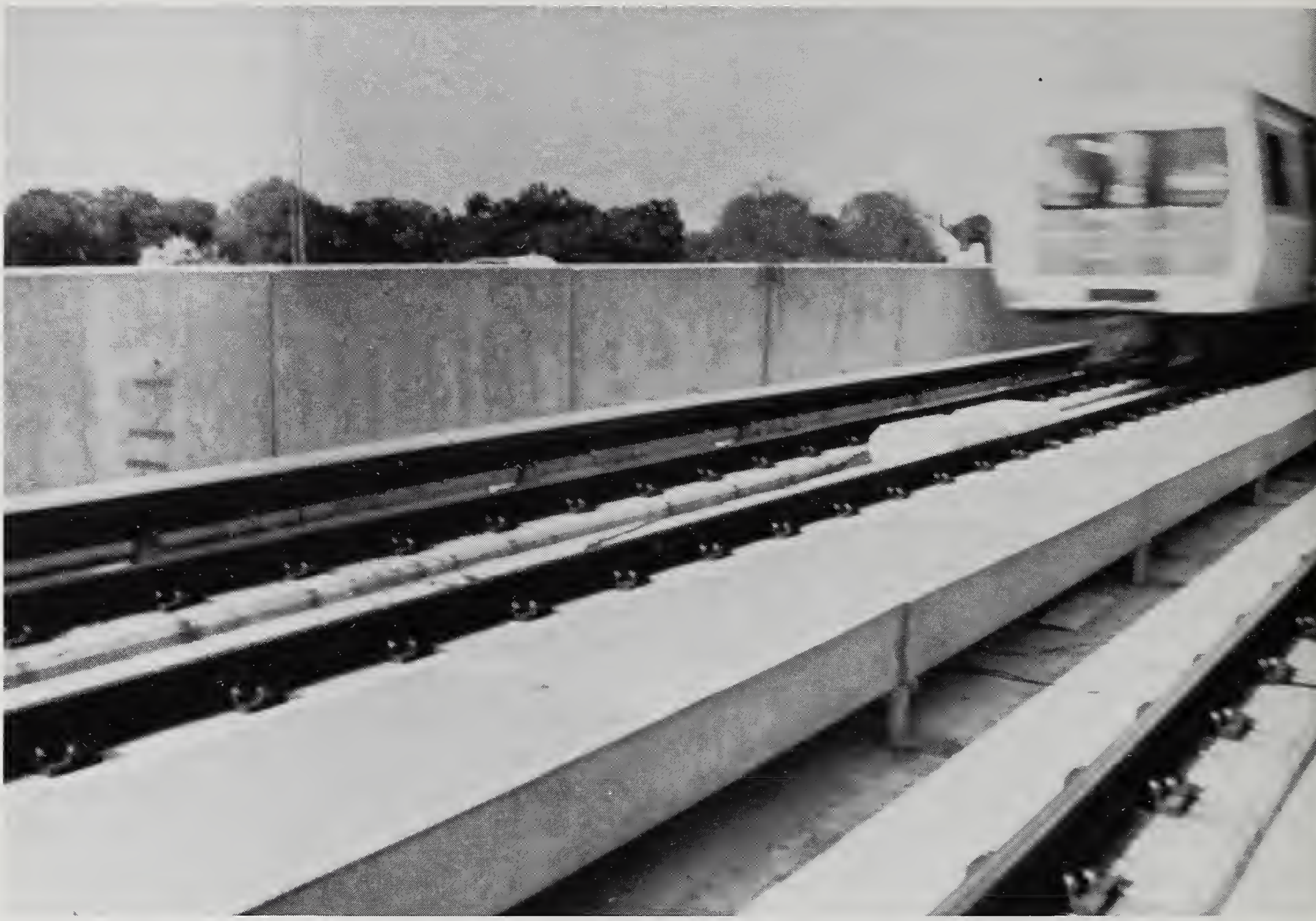
Although floating slabs represent the most effective technique for reducing the transmission of vibration, their installation is currently expensive, and more cost-effective designs are needed. To address this need, research on the use of floating slabs has been conducted. (30) A model was developed to predict the reduction in vibration transmitted from the rails to the tunnel floor obtained with floating slabs. A second part of the research effort involved a field study of floating slab track undertaken in cooperation with the NYCTA. The effectiveness of floating slabs in reducing vibration transmitted to the tunnel floor and walls was evaluated. Data collected included measurements at several points on the slab, on the tunnel wall, and on the tunnel floor. Vibration levels produced along floating slab track were compared with those produced along conventional track for the same train pass-bys. One of the study findings was that "floating ties," which consist of heavy concrete ties supported by resilient materials on the tunnel floor, could be just as effective as continuous floating slab.

A number of rail fastening systems are currently available commercially. To provide a basis for selection among these systems, a study is now being formulated which will compare the cost and performance of various systems. The acoustic and vibration characteristics of the following systems will be compared: standard wood ties on ballast, wood blocks cast into the concrete invert (tunnel floor), concrete ties on ballast, resiliently supported concrete ties, and resilient fasteners directly fixed to a concrete tunnel floor. Data on each of these systems also will be compared with the data previously obtained on the performance of floating slab track systems.

Propulsion System Noise

Noise from the operation of propulsion system equipment, particularly traction motors and gearboxes, is now recognized as a substantial contributor to urban rail transit noise. Noise from the propulsion system, particularly from the motor cooling fans, increases with train speed more rapidly than does wheel/rail noise. Recent tests on SEPTA and NYCTA have indicated that on older model transit cars, propulsion system noise can exceed wheel/rail noise at speeds as low as 30 mph. On newer systems where continuous welded rail and other wheel/rail noise abatement techniques are employed and where train operating speeds are typically higher, propulsion system noise is again often the dominant noise source.

Research is planned to develop and demonstrate a technology for retrofitting existing vehicles in order to abate propulsion system noise. This will be accomplished through a three-phased effort: first, the specific noise-generating



Barrier walls used on new systems help reduce the impact of propulsion system noise on the wayside community.

sources in propulsion systems will be identified; second, various techniques for controlling these sources will be evaluated; and finally, the best techniques will be demonstrated through in-service testing.

Several techniques to control the propagation of propulsion system noise away from concrete elevated structures were recently investigated. The new transit system under construction in Dade County, Fla., includes extensive mileage on concrete elevated structures. Indications from recent studies are that propulsion system noise levels on concrete elevated structures are 5 dBA higher than levels on at-grade ballasted track due to a lack of absorptive materials under the car. Dade County is planning to use acoustical barriers to reduce noise levels along elevated structure route mileage. However, it was believed that the use of vehicle "skirts" might provide a more cost-effective solution. Vehicle skirts, which extended from the car body down over the wheels, act to block noise radiation from the undercarriage area.

A study was undertaken by UMTA to investigate the relative effectiveness of these techniques and to obtain technical information useful in future propulsion system noise control efforts. Results of scale model tests showed that vehicle skirts in combination with undercar absorptive treatment provide 5 dBA reduction in propulsion system noise on concrete elevated structures. Based on these initial tests, it was estimated that the use of vehicle skirts and undercar absorption in Dade County would cut the need for acoustical barriers in half, resulting in potential savings of $3 million.

3. Technology Deployment

The primary goal of the Urban Rail Noise Abatement Program is the deployment or implementation of cost-effective noise abatement techniques on U.S. transit systems. In order for research and development activities to result in implementable products, on-going communication must be maintained with potential users and suppliers of noise abatement treatments. Periodic review of research and development activities by users and suppliers can provide valuable input in the form of technical, operational, and economic data to guide research and development activities in a productive manner.

The participation of APTA in an advisory capacity in the Urban Rail Noise Abatement program provides one method of communication with the U.S. transit industry. The APTA Advisory Board, with representatives from all 10 urban rail transit properties, meets approximately twice a year. The board reviews draft documents and final reports of program activities. In addition, APTA and UMTA jointly sponsor a seminar at the completion of each major research and development project to present project results. Attending these seminars are Advisory Board members, equipment suppliers, public officials, and consultants. The results of the SEPTA in-service testing of wheel/rail noise abatement techniques were presented in Atlanta, GA, in December 1979. A slide-tape show on the in-service testing was part of the presentation.

Research results are also disseminated through technical reports, distributed by UMTA to transit properties, consultants, government officials, and suppliers. The general public may obtain these reports through the National Technical Information Service (NTIS).

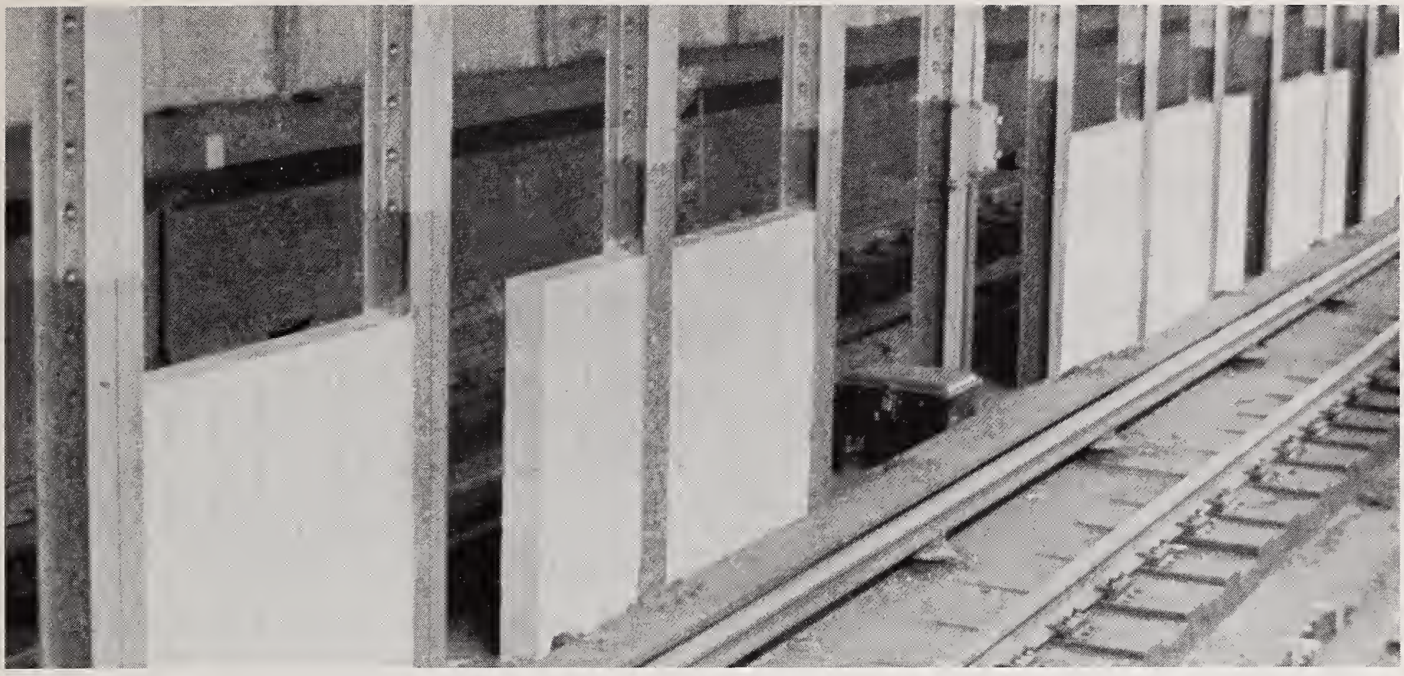
Newly-constructed systems are designed to include current noise abatement treatments.

A more direct exchange of information between UMTA and transit properties is planned through a traveling road show, which will visit all the major transit properties. Attending these meetings will be transit management and technical personnel, and members of the general public. Audio-visual presentations will be used to describe program activities and to explain the urban rail noise generation process. Various technical, planning, and institutional factors affecting implementation of noise abatement techniques will be discussed among those attending. UMTA/TSC staff will have an opportunity to learn about local experiences with noise abatement while at the same time disseminating information on program-sponsored activities.

The Department of Transportation's Transportation Systems Center (TSC) will play an increasing role in the exchange of information on urban rail noise abatement. In the past TSC has planned and implemented the research program and has acted as technical monitor for research projects funded through the Urban Rail Noise Abatement Program. In this capacity, TSC staff have also provided technical assistance on noise abatement to transit properties and have acted as an informal clearinghouse on urban rail noise abatement information. TSC is currently formulating a plan to collect, store, and retrieve pertinent information regarding urban rail noise activities. Organizations involved include transit properties — both domestic and foreign — consultants, universities, suppliers, private companies, community organizations, and government agencies. The first phase of this information program will utilize a library-type filing and retrieval system. The second phase will utilize a computerized data base management system. Additionally, TSC will maintain a technical data information file and a catalogue of technical references. All of this information will be available to those working in the area of urban rail noise abatement.

The actual implementation of noise abatement programs by transit authorities presents various technical and institutional difficulties. Under the Urban Rail Noise Abatement Program, several tools are being developed to aid in noise abatement planning and implementation. The profusion of recent literature makes it difficult for transit authorities to select and implement available technology for noise and vibration control. A *Handbook of Urban Rail Noise and Vibration Control* is being developed to summarize the literature in a form usable by transit authorities, as well as by suppliers and consultants. Topics covered include fundamentals of sound and vibration, measurement techniques, acceptability criteria, noise control actions required for new and for older systems, techniques recommended for control of vehicle, station, wayside, elevated structure, and groundborne noise and vibration, as well as several case histories of noise control actions undertaken by different transit authorities. Two editions of the handbook are planned. The first, to be published in 1980, will summarize the most useful rail transit noise control data and procedures currently available. A second edition will expand and update the first to include future results of the program. In each case, the handbook will be distributed at an invitational seminar during which the content will be discussed and specific uses will be suggested.

Noise abatement planning is not dependent solely upon the state of available noise control technology. The planning of such improvements is influenced by the concerns of transit authorities, the public, and various local, state, and federal agencies, as well as by available funding. In order to aid transit authorities in their planning efforts, a *Noise Abatement Planning Handbook* is being prepared which will identify and explain the elements necessary for comprehensive noise abatement planning, describe available resources, e.g. computer planning tools and potential funding sources, and present selected case histories of noise control planning by transit authorities. As part of this activity a computer program is being developed which will aid in the determination of the most cost-effective systemwide noise abatement strategies. This "Procedure for the Evaluation of Abatement Cost-Effectiveness" (acronym PEACE) is based on the cost-effectiveness methodology developed



Older stations can be acoustically upgraded with installation of noise control treatments such as sound-absorbing barriers, resilient rail fasteners, and welded rail.

as part of the assessments, in particular a refinement of this methodology done for the NYCTA.

In addition to the handbooks, a *Compendium of Acoustical Materials* for use in rail transit systems is planned as an aid to transit operators responsible for implementation of noise control.

The exchange of technical information with others engaged in urban rail noise abatement research and research in related fields, such as acoustics, is an important component of the research and development process. Participation by TSC personnel in various professional and trade organizations is one means to this end. In the past TSC personnel have presented papers at the International Conference of Noise Control Engineering (INTER-NOISE) and at the National Conference of Noise Control Engineering (NOISE-CON), as well as participating in two International Workshops on Railway and Track Transit System Noise. Representation on the Noise Committee of the International Union of Railways has been a valuable source of information on European railway noise research. The publication of research results by TSC personnel in technical journals provides another avenue of communication.

The greater the overall awareness about the activities of the Urban Rail Noise Abatement program, the more effective the program can be. The traveling road show, described earlier, will acquaint broader numbers of people with the program. Other efforts to publicize the program include a brief program summary and this state-of-the-art overview.

Inquiries about program activities, products, and future plans are invited and should be directed to:

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Glossary

APTA
American Public Transit Association

A-weighted decibel
A measure of sound which weights the various frequencies comprising a sound in a manner which approximates the perceptions of the human ear.

BART
Bay Area Rapid Transit District

Bogie
A transit car undercarriage which swivels so that curves can be negotiated

Crabbing
An alternate rolling and sliding of the wheel along the rail which occurs as a train rounds a short radius curve

CTA
Chicago Transit Authority

Damped wheels
Standard wheels retrofitted with a damping device to reduce vibrations

dBA
See A-weighted decibel

Dynamic braking
Use of the traction motors as generators, thus creating a drag on the train

Floating ties
Heavy concrete ties supported by resilient materials on the tunnel floor

Floating slab track
Rail mounted on concrete slab trackbed which in turn is isolated from the tunnel floor by resilient pads

Girders
The horizontal beams of an elevated structure, which act as the main support for the roadbed

Impact noise
An impulsive noise produced by wheels encountering discontinuities, such as rail joints or flat spots on the wheels themselves

Jointed rail
Rail laid in segments producing a slight gap in the rail where segments meet

L_A(MAX)
The maximum A-weighted sound level occurring over a period of time.

MBTA
Massachusetts Bay Transportation Authority

NYCTA
New York City Transit Authority

PATCO
Port Authority Transit Corporation

PATH
Port Authority Trans-Hudson

Rail corrugation
Periodic irregularities in the rail surface produced during wear

Rail joint
The point at which the ends of rail segments meet

Resilient rail fastening
A method of rail fastening wherein pads of resilient material are placed between the rail and the roadbed

Resilient wheel
A wheel manufactured with a resilient material between the tire and hub that acts to damp vibration

Ring-damped wheels
Standard wheels retrofitted to reduce vibration by means of a metal ring snapped into a groove cut in the wheel tread

Roar noise
A continuous noise caused by small-scale roughness on wheels and rails

Route miles
Mileage measured according to the length of the transit line regardless of the number of tracks

RTA
Greater Cleveland Regional Transit Authority

SEPTA
Southeastern Pennsylvania Transportation Authority

SIRTOA
Staten Island Rapid Transit Operating Authority

Squeal noise
A sharp high-pitched noise produced by the alternate sticking and slipping of wheels as they pass through short radius curves

Step-down joint
A rail joint where the second rail end (in the direction of the train's travel) is lower than the first

Step-up joint
A rail joint where the second rail end (in the direction of the train's travel) is higher than the first

Tangent track
Straight track

Tread braking
Application of brake shoes to the outer surface of the wheel in order to slow the train down

Truck
The frame and wheel assembly which supports the transit car body, with one truck at each end of the car

Tunnel invert
Concrete tunnel floor with a recessed area which contains the track

Wayside noise
Noise experienced in communities located along side transit rights-of-way

Welded Rail
Rail with a continuous unbroken surface due to the welding together of the ends of rail segments

Wheel flats
Flat spots on the wheel's rim caused by locking of the wheel during braking

Wheel squeal
See Squeal noise

Wheel truing
Machining wheel tire surfaces to remove irregularities created during train operations

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Reports on UMTA research and development described in this volume are available to the public through the National Technical Information Service (NTIS). NTIS is the principal repository and disseminating agency for all reports issued in conjunction with federal research and development activities. To order reports from NTIS use the order numbers ("PB" numbers) listed after each report citation in the bibliography. The lack of an order number following the citation means that the report had not yet been entered into the NTIS system when this publication went to press.

Inquiries about the availability or price of reports should be addressed to NTIS, rather than UMTA. The NTIS Order Desk telephone number is (703) 557-4650. Payment must accompany orders; cash, check, postal money order, GPO coupons, or American Express are acceptable. It is possible to establish an account at NTIS, from which payments are withdrawn when documents are ordered.

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